NIOSH

SAFETY IN MANUAL MATERIALS HANDLING

Report on International Symposium:
Safety in Manual Materials Handling
State University of New York at Buffalo
July 18-20, 1976

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PREFACE

This book had its antecedent in the International Symposium: Safety in Manual Materials Handling, held at State University of New York at Buffalo (NY) in July 1976. The antecedents to that Symposium were the NIOSH Workshop on Criteria for Research on the Hazards of Manual Materials Handling, the report on the Workshop by G.D. Herrin, D.B. Chaffin, and R.S. Mach, and an idea that international coordination and input were a necessary next step in alleviating what is essentially an international problem.

The structure of this book reflects to some extent these antecedents; it also has obvious similarities to an earlier symposium on a different topic organized by the editor in 1974 (see Human Reliability in Quality Control, C.G. Drury and J.G. Fox, editors, Taylor & Francis, 1975). Both this source and the NIOSH report referred to above shaped the symposium that was seen as an orderly exposition of the field leading to specific research recommendations.

When the authors were contacted and asked to review specific areas, many commented that what I requested was useful and even interesting but what I *really* needed to have presented at the symposium to make it a success was . . . . And they suggested other relevant subjects or pieces of research. These eventually became a series of *ad hoc* papers, presented in an informal atmosphere late one evening during the symposium. It was in this session that some particularly interesting new ideas emerged. These *ad hoc* papers have been incorporated in this book in (what I consider to be) an appropriate place. Hence, the book reflects the original organization of the symposium with some of the editor's areas of ignorance relieved by hindsight and by courtesy of many authors.

No attempt is made in the book to provide verbatim reports of the question and answer periods after each paper. Rather these discussions have been edited into the introduction and summary of each Chapter and have been used to help edit the papers themselves. Liberties have also been taken with the papers, particularly to avoid unnecessary overlap in introductions and coverage of basic methodologies. Specific authors have also been asked to expand their papers to cover points that slipped between authors and were missing from the symposium. The reader can be assured that *all* of this highly selected assembly of authors know the background material to their subject.

Neither the symposium nor this book could have been produced without help. The support of NIOSH and the SUNY Conferences in the Disciplines Fund need especially to be acknowledged. In particular, their representatives in the persons of D. W. Badger and W. H. Baumer were most helpful and encouraging.

On the SUNY Buffalo campus, special thanks must go to Ethel E. Schmidt of the SUNY Conference office for the lion's share of the Symposium organization; to Warren H. Thomas, Chairman of Industrial Engineering, for enthusiastic support of a field far removed from his usual academic pursuits; and to Pat Saltzman and Terri DeGeorge for shouldering the burden of the editorial typing. The diagrams were redrawn for publication by Ruth Schultz and Barbara Evans. Marion Curry and Dan Habes of NIOSH shepherded this volume through the editorial process to the printing.

Finally, I should like to acknowledge the forbearance of the authors represented in this book; their contributions are the meat on the bones of an idea.

C.G.D.
Buffalo, N.Y. 1977

ABSTRACT

The problem of injuries from manual materials handling in industry has shown little improvement over many years; the injuries account for 20% to 30% of all injuries in many countries. During 1974, a NIOSH committee produced a report (CDC-99-74-118, Herrin, Chaffin, and Mach) outlining future research needs in this area. These research needs were only able to be prioritized in a relatively simple manner at the time. Following this report, the need was felt for a mechanism to obtain national and international input to help shape NIOSH research policy in the field of Manual Materials Handling Safety. The mechanism chosen to obtain this input was an International Symposium: Safety in Manual Materials Handling, which was held at the State University of New York at Buffalo in July 1976.

The objectives of the symposium, and of this book reporting its findings, were two-fold:

- to present a logical and consistent framework for summarizing current knowledge in the field;
- to utilize the expertise of the international community to prioritize future research by NIOSH within the context of research proceeding in other countries.

These objectives were accomplished by inviting respected members of the research and safety communities to review parts of the field, thus presenting current knowledge in a coherent manner. Twenty-four papers were presented. These began with an overview of the needs of NIOSH, proceeded through a review of the sub-systems of the body stressed in these tasks, continued with numerical models of human performance and safety, reviewed the factors that can affect performance, and ended with problems of implementation of research. In addition to the speakers, other prominent figures in the field were invited to chair sessions and lead workshops. A number of industries also sent representatives.

The research areas above are presented as chapters in this book, with a final chapter summarizing the results of three goal-oriented workshops that took place on the final day of the symposium. The findings of these workshops are summarized in the final recommendations.

It is recommended that any future safety standard must include, as a minimum, the weight, size, and position of the load handled and its frequency of handling, as well as indicate which loads need preplacement testing of workers. Future research needs are for improved diagnosis, reporting and job description procedures, new epidemiological studies to determine the effect of particular factors, and studies to enable the effectiveness of any proposed standard to be estimated.

CONTENTS

CHAPTER 1

THE MANUAL MATERIALS HANDLING SAFETY PROBLEM

INTRODUCTION

It has been known for a generation that manual materials handling is a real and continuing industrial hazard. This knowledge has been accompanied by analyses of accident statistics, published case histories from both industrial and general medical practitioners, lofty research from biomechanics to blood pressure, and many, many advocated methods of safe lifting. It has also spawned poster campaigns, safety films, training schemes, and notices in the classified advertisement columns of newspapers offering relief from the pain after an incident has occurred. What has been notably absent is a steady reduction in either total manual materials handling injuries or the percentage of general injuries caused by manual materials handling.

J. R. Brown, whose annotated bibliography (1972) is a comprehensive and often penetrating starting point for literature searches in the field, claims that both the content and application of our intervention strategies have been misguided. It is the major aim of this volume to bring together the various lines of research from around the world into expert recommendations for effective intervention in the future.

The most famous meeting of experts to consider this problem was that organized by the International Labour Organization, which published (1964) its Maximum Permissible Weight to be Carried by One Worker. Since their rather reluctant recommendation of 40 to 50 kg (84 - 110 lb) for adult males, based on standards obtained in many countries and the then-available research results, authors and organizations have been noticeably hesitant about putting a single number into print to cover the complexities of the problem. Why has this been so?

Firstly, there is the very real question of what constitutes an accident or even an injury. A comprehensive study by the National Institute of Industrial Psychology in the United Kingdom (Powell et al., 1971) showed that reported accidents are a very biased sample of accidents. To quote J.D.G. Troup, whose paper appears in Chapter 2 of this volume:

> "Statistics from official sources and retrospective reviews of handling injuries and strains either from industrial or hospital records are, therefore, a waste of time."

Fortunately, other methods are available, if somewhat more costly.

Secondly, there is the multiplicity of ways in which manual materials handling tasks can overstress the worker. Low back pain resulting from overstress of the spine during lifting is only one of many ways to injury even though it is numerically an important one. Other examples would be overstress of the muscles, the heart-lung-circulation system, or the thermo-regulatory mechanisms resulting from prolonged high-intensity manual materials handling work.

Thirdly, there is the sheer complexity of factors affecting manual materials handling performance and safety. Individual strength, age, and sex; details of workplace and container design; type of task performed, such as lifting, pushing, carrying, etc.; and environmental characteristics all help determine what is a "safe" weight.

Finally, the setting of standards or guidelines is not the only way of alleviating the problem. Worker placement and training and broader guidelines for job design are also possible.

In fact, all of these intervention strategies can be the subject of standards and guidelines at local, state, federal, or international level. The purpose of this international symposium (International Symposium: Safety in Manual Materials Handling held at the State University of New York at Buffalo in 1976) was to produce definite recommendations on the immediate research required to set such standards. With manual materials handling injuries consistently accounting for 20% to 30% of all industrial injuries from the United Kingdom to Minnesota (Brown, 1972), international input from Western Europe and Canada was deemed essential.

The specific form of the symposium, and of this book based on it, is a review of the research findings and methodologies as a necessary preliminary to defining research needs. Participants had the benefit of a weighty set of research recommendations made by a NIOSH-sponsored panel of experts in 1974 after an in-depth study of the problem (Herrin, Chaffin, and Mach, 1974). Herrin's paper in this chapter gives a succinct appraisal of this work and its results. One result was an organized framework or taxonomy of the field, which proved to be the prototype for the framework of this book.

The task set to the forty-odd experts at this symposium was to order and prioritize the Herrin, Chaffin, and Mach (1974) recommendations or to substitute others based on a year of hindsight since those recommendations were made. The results of the workshops are presented as part of Chapter 6 of this volume.

By way of introduction to the two papers presented in this Chapter, Dukes-Dobos shows clearly what approach NIOSH means to take to the problem, particularly in the area of low back injuries associated with lifting. Herrin, in addition to reviewing previous work, demonstrates what is required to bring some degree of epidemiological rigor to the study of manual materials handling injuries.

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ACCIDENTS, INJURIES, AND STANDARDS

F. N. Dukes-Dobos

The Occupational Safety and Health Act of 1970 (OSHAct) gave the National Institute for Occupational Safety and Health (NIOSH) the responsibility to perform research for the purpose of recommending safety and health standards. The promulgation of the recommended standards to mandatory standards and their enforcement was made the responsibility of the Occupational Safety and Health Administration (OSHA). This division of responsibilities gives NIOSH a certain amount of independence so it can concentrate its research efforts on establishing human tolerance limits to the physical and chemical agents of the work environment independent of the economic impact of these limits should they be promulgated as mandatory standards. However, the OSHAct stipulates that the standards must be practically feasible, and this has not been disregarded in any NIOSH recommendation. Differences of opinion, of course, are inevitable in issues of such complexity as mandatory safety and health standards, but each NIOSH recommendation must pass several review procedures before it is forwarded to OSHA. The review committees include representatives of all interested parties, i.e., government, industry, unions, academic institutions, and those who will be responsible for compliance at the shop floor.

Accordingly, to recommend a safety and health standard for manual materials handling, first, we have to establish human tolerance and capacity limits and, second, we have to come up with practically feasible provisions to make sure that they will be acceptable to all parties involved.

After several consultative meetings with the experts in this field, it became apparent that the cause-effect relationships in injuries that occur in manual materials handling jobs are not well established. But there is one point on which most experts agreed, namely that the target of injuries in materials handling jobs is most often the lower back and that this type of injury is brought about most often during lifting activities.

It now occurred to us that the most profitable approach to reducing the number of injuries in materials handling jobs should be to concentrate on assessing human tolerance to lifting of objects.

The question can be formulated this way: How much weight can be lifted without low back injury? The complexity of this question is well known to the participants of this symposium. As a matter of fact, each of the participants will talk about a different facet of this problem.

However, when we talk here about lifting injuries, let us avoid the mistake of overemphasizing certain aspects of the back injury problem and underemphasizing others. Besides the question of human tolerance to lifting, there are a multitude of environmental and behavioral factors that may be just as important in the causation of injury. Therefore, if back injuries are to be diminished substantially, there is a need for cooperation between the safety engineer and behavioral scientist on one hand, and the experts in the different disciplines of ergonomics on the other. This latter includes experts in biomechanics, work physiology, industrial engineering, and in the different branches of medicine, particularly orthopedics.

This symposium was convened as an interdisciplinary forum to clarify problems related to establishing human tolerance limits to lifting, as well as to examine the usefulness of different practical measures that have been proposed for preventing back injuries. The latter aspects, namely, the question of practical preventive measures is a very controversial issue. Recently, we have noticed a worldwide rise in journal articles, pamphlets, etc., recommending certain lifting techniques for the prevention of back injury. Different techniques are described by experts in different countries as being the safest. Unfortunately, there is little evidence on which one could judge the validity of these claims. Perhaps each method may be advantageous under specific conditions.

Miller (1976), in an article on back pain, reported that in New Zealand Leonard Ring introduced a new lifting technique among dock workers by which he achieved a 50% reduction in back injuries. This claim is certainly amazing and commands attention. However, some important questions have to be raised: What other preventive measures were simultaneously introduced with teaching of the new techniques? Was there some sort of selection of workers? How much of the success was due to a greater safety awareness after the education program? Unfortunately, Mr. Ring is not here to answer these questions, but the same questions can be asked in connection with other similar claims. For instance, the claim of Allen Fischer, who, when demonstrating his apparatus for screening applicants for materials handling jobs, stated that none of the workers who were found acceptable by his screening method suffered back injury on their jobs. He also distributed flash cards very skillfully showing the lifting technique he believes to be the correct one. The point that must be made here is that by overemphasizing "safe" lifting techniques, we may bring about a climate of relying too much on methods of lifting, while forgetting other preventive measures that, according to available evidence, may be at least as important for the prevention of back injuries.

Coming now to the question of standards, we must ask ourselves: What kind of a standard can be envisioned for manual materials handling and when will our knowledge reach the stage where we will have enough evidence to satisfactorily support our recommendations?

The present philosophy in NIOSH is that one does not have to wait to recommend a standard until everything is known about a potentially harmful agent, as long as there is enough evidence for supporting permissible limits and for proving the efficacy of certain preventive measures. In other words, a standard can be recommended in which the existing gaps in our knowledge are clearly identified. By doing so, we put into action existing knowledge for the benefit of the worker and society, and at the same time, we are setting up the tasks for scientists to perform further research in the gap areas.

Many representatives of industry are against setting safety and health standards because they fear that compliance will be too costly. They tend to forget the increasing cost of insurance and workers compensation. However, some industries as well as insurance companies have established their own safety codes for lifting work and found the expense of their preventive measures to be a good investment. Some industries select workers by preemployment medical examinations including testing of physical fitness, others have mandatory training procedures, and a few have established their own maximal weight limits for manual materials handling.

This brings us to one of the most important questions, i.e., whether or not a maximum permissible weight for lifting and/or carrying should be made mandatory in view of the great individual variability among workers. One possible approach to overcome this problem is to give guidelines for maximum loads that can be lifted without excessive strain by different percentiles of the worker populations, similar to those of the Ergonomics Committee of the American Industrial Hygiene Association prepared by Stover Snook (1970). If a single weight would be set as maximum permissible limit, as it has been done by ILO or by several states in the United States, then unnecessary restrictions would be imposed on the stronger worker while the weaker ones would still remain unprotected. This approach of different guidelines for different workers is based on the theory (now under investigation by Don Chaffin under NIOSH sponsorship) that the risk of back injury increases if a worker lifts weights heavier than would be commensurate with his or her muscular strength. As a result of this theory, muscular strength measurements would be made before employing workers in jobs requiring lifting. But can we make preemployment muscular strength measurements mandatory with the present state of availability of equipment and know-how in industry? We understand that in some major industrial plants such measurements are being done, but whether this can be made mandatory for all lifting jobs is another question. The answer depends to a great extent on the evidence — how effective would this measure be in preventing low back injury? If muscular strength would turn out to be the key to the problem, then ways would have to be explored to make testing equipment and know-how available where required.

The issue becomes more complicated, however, when the limits are examined from the point of view of protecting female workers against damage to their reproductive organs, a question which has been loudly raised recently. According to a review paper by Theodor Hettinger (1971), the limiting factor, when women are performing lifting tasks, is not muscular strength by gynecological considerations, such as the effect of increased abdominal pressure during lifting on the position of the uterus.

As if all this were not complicated enough, we cannot dismiss the role of the cardiovascular and skeletal system in determining the maximum permissible weights, particularly in the older worker who suffers from arteriosclerosis and whose vertebral discs are losing their elasticity.

In spite of the many unanswered questions in relation to a standard for manual materials handling, a tentative list of items to be included can be prepared. At the top of the list is selection of workers for lifting jobs; then follows training, guide for permissible weights in view of the frequency and nature of the lift and carrying distances, work-rest regimens, container shapes and sizes, and last, but not least, safety management practices. This sounds like the program of this symposium. What it proves is that Dr. Drury and Dr. Badger have done their homework very well in preparing this symposium.

It is most fortunate that we have participants here who have brought with them not only results of laboratory studies, but also a thorough knowledge of the workplace. Perhaps we can find the most valuable source of information for a standard right in the medical and industrial hygiene departments of industries where the battle of decreasing the number of back injuries has been fought with more or less success for many years. We open our doors for cooperation, and we hope that industry will do the same. It is in the interest of all to make sure that a practical standard, or a guide, or both should be based on the best available knowledge.

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A TAXONOMY OF MANUAL MATERIALS HANDLING HAZARDS

G. D. Herrin

The dimensions of the problem and the issues surrounding the channeling of research in the complex field of manual materials handling (MMH) hazards are considerable. Recently, a group of informed researchers gathered to consider the potential hazards and to:

- provide a critique of the published literature to identify the state of knowledge,
- define specific gaps in present knowledge, and
- develop criteria upon which future programs of research on hazards of MMH can be based.

This paper presents an overview of the efforts of these experts (Herrin et al., 1974) and recent example implementations of their recommendations at the University of Michigan (Chaffin et al., 1976; Chaffin and Herrin, 1976; Chaffin and Park, 1973).

PROBLEM TAXONOMY

To provide a workable critique of those factors which characterize this problem area, a taxonomy is helpful. In essence, four major components of the MMH system need to be recognized. These (illustrated in Figure 1) include the characteristic of the worker, the task, the material/container, and the work practice. Central to the interfaces of these system components are the hazard measures or indices that reflect the deleterious effects of inappropriate matches among the system components.

A variety of measures of hazard have been proposed in the literature; these may be broadly classified as injury/illness effects, physiological effects, and behavioral effects. The variables within each of these classes are defined in Table 1. Few researchers have considered more than one of these variables at a time. Although, from a practical standpoint, this is often necessary, it does not point out the multivariate dimensions of the hazard phenomena. There is also an apparent heirarchy of measures—from the tangible, easily quantifiable to the more abstract and difficult to measure. Unfortunately, measurable does not necessarily imply meaningful, nor can measurable variables necessarily be optimized or suggest remedial action.

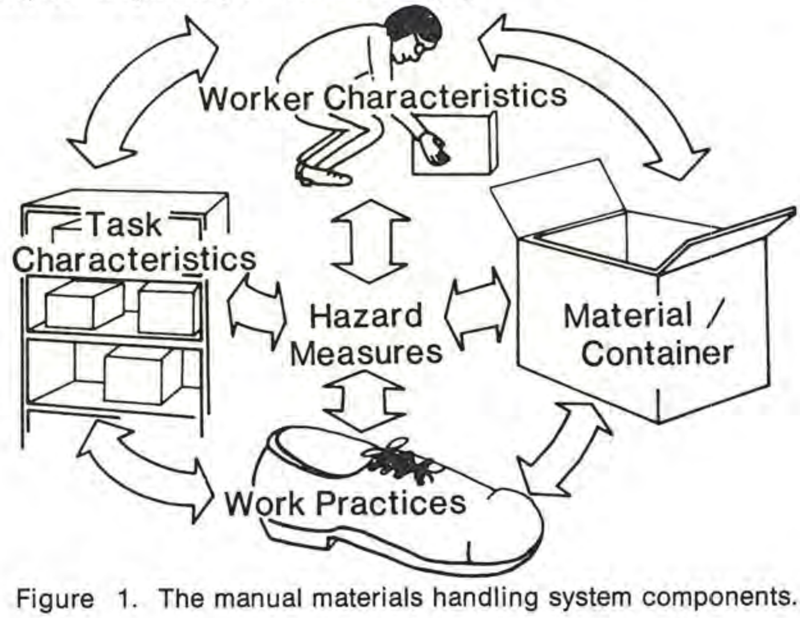

Figure 1. The manual materials handling system components.

Table 1. A list of the hazard indices relating the adverse effects of manual materials handling.

INJURY AND ILLNESS EFFECTS

SEVERITY: measures of the severity of a specific type of injury or illness, such as: lost time; time on medical work restriction; compensation costs; medical treatment costs; lost employment.

FREQUENCY: measures of the rate of occurrence of a specific type of injury or illness, such as: injury incidents per million man hours; injury incidents per job classification.

PHYSIOLOGICAL EFFECTS

CIRCULATORY/PULMONARY: measures of the responses to manual materials handling, such as: heart rate; cardiac output; blood pressure; aberrations in myocardial functions (EKG); alterations in respiration; peripheral blood flows.

MUSCLE METABOLISM: measures of the steady state and transient metabolic responses to manual materials handling, such as: oxygen uptake rates; caloric costs; body temperature changes; hormonal shifts; plasmic constituents; enzyme levels.

BIOMECHANICAL: measures of the biomechanical stresses and strains, such as: forces and/or pressures associated with tissues of the musculoskeletal system; rotational moments and/or torques at various articulations; EMG and kinesiological indications of muscle loads and fatigue states; altered radiographic findings in tissue following manual materials handling.

NEUROMUSCULAR AND NEUROLOGICAL: measures of the neurologic responses associated with manual materials handling, such as: slowed neural conduction velocities; altered motor unit behavior as indicated by EMG changes; altered reflexes; abnormal sensory functions.

BEHAVIORAL EFFECTS

PSYCHOLOGICAL: measures of the mental states of workers during and after manual materials handling activities, such as: MMPI profiles; clinical ratings of trauma-induced neurosis; attitudinal indices; attribution scales.

PSYCHOPHYSICAL: measures of the psychological acceptability of manual materials handling activities, such as: tolerance of physical exertion; physical discomfort ratings; perception of unsafe physical acts or risk-taking behaviors in such acts.

SOCIOLOGICAL: measures related to the social responses of people associated with manual materials handling, such as: turnover rates; absenteeism attributed to work environment; antisocial behavior patterns.

In Table 2 are a list of the various factors comprising the identifiable system components. This collection of variables illustrates the even greater number of factors that may be the contributors to hazard potential. At present, each of these factors has been studied (in varying details) singularly; few studies have explored the variables collectively (beyond two or three variables at a time).

To identify the gaps in knowledge related to this taxonomy of hazard measures and system components, a sample of 208 published articles was critiqued. The numbers of articles that examined particular combinations of hazard and system measures are tabulated in Figure 2. One obvious point can be drawn from this tabulation of 20 system characteristics: rather than having "gaps in knowledge" associated with the hazards of MMH, it may be more candid to point out the "islands of knowledge."

Although over half (115) of the articles cite load (or object weight) as being an important variable under investigation across the hazard measures, we have no agreement on how much a person can safely lift. This is, of course, due to the realization that criteria for load (in this case) cannot be determined independent of each of the remaining 19 system characteristics. Nor can any criteria be expected to satisfy all levels of the hazard indices.

To expand knowledge of the hazards of MMH, a number of unidimensional probes will be necessary. The following collection of research needs are recognized in the literature and by the aforementioned panel of experts as having a substantiated need, adequate substantive knowledge, well developed methods, and clearly visible, easily identified available resources.

Table 2. The various factors comprising each of the four major manual materials handling system components.

WORKER CHARACTERISTICS

PHYSICAL: general worker measures, such as: age; sex; anthropometry; postures.

SENSORY: measures of worker sensory processing capabilities, such as: visual; auditory; tactual; kinesthetic; vestibular; proprioceptive.

MOTOR: measures of worker motor capabilities, such as: strength; endurance; range-of-movement; kinematic characteristics; muscle training state.

PSYCHOMOTOR: measures of worker capabilities interfacing mental and motor processes, such as: information processing; reaction/response time; coordination.

PERSONALITY: measures of worker values and job satisfaction by attitude profiles; attribution; risk acceptance; perceived economic need.

TRAINING/EXPERIENCE: measures of the worker education level in terms of formal training or instruction in manual material handling skills; informal training; work experience.

HEALTH STATUS: measures from worker general health appraisal, such as: previous medical complaints; diagnosed medical status; emotional status; regular drug usage; pregnancy; diurnal variations; deconditioning.

LEISURE TIME ACTIVITIES: measures of the persons choosing to be involved in physical activities during leisure hours, such as: holding a second job or regular participation in sports.

MATERIAL/CONTAINER CHARACTERISTICS

LOAD: measure of mass; pushing/pulling force requirements; mass moment of inertia.

DIMENSIONS: measures of size of unit workload, such as: height; width; breadth when indicating the form of rectangular, cylindrical, spherical, etc.

DISTRIBUTION OF LOAD: measure of the location of the unit load CG with respect to the worker for one-hand and two-handed carrying.

COUPLINGS: measures of simple devices used to aid in grasping and manually manipulating the unit load, such as: texture; handle size, shape, and location.

STABILITY OF LOAD: measures of load CG location consistency, as a concern in handling liquids and bulk materials.

TASK CHARACTERISTICS

WORKPLACE GEOMETRY: measures of the spatial properties of the task, such as: movement distance; direction and extent of path; obstacles; nature of destination.

FREQUENCY/DURATION/PACE: measures of the time dimensions of the handling task including frequency, duration, and required dynamics of activity over the short term and long term.

COMPLEXITY: measures of combined or compounding demands of the load, such as: manipulation requirements of movement; objective of activity; precision of tolerance; number of kinetic components.

ENVIRONMENT: measures of added deteriorative environmental factors, such as: temperature; humidity; lighting; noise; vibration; foot traction; seasonal toxic agents.

WORK PRACTICES CHARACTERISTICS

INDIVIDUAL: measures of operating practices under the control of the individual worker, such as: speed and accuracy in moving objects; postures (i.e., lifting techniques) used in moving objects.

ORGANIZATIONAL: measures of work organization, such as: physical plant size; staffing of medical, hygiene, engineering, and safety functions; and utilization of teamwork.

ADMINISTRATIVE: measures of administration of operating practices, such as: work and safety incentive system; compensation scheme; safety training and control; hygiene and safety surveys; and medical aid and rescue; long work shifts; rotation; personal protective devices.

			System Characteristics																					
			worker								material/ container					task				work practices			
			Physical	Sensory	Motor	Psychomotor	Personality	Training	Health Status	Leisure Activity	Load	Dimensions	Distribution	Couplings	Stability	Workplace Geom.	Frequency/Pace	Complexity	Environment	Individual	Organizational	Administrative	Totals
Hazard Indices	injury	Severity	11	0	1	1	5	2	14	0	8	2	1	0	2	0	0	0	1	4	1	3	56
		Frequency	18	1	4	1	5	5	22	0	24	7	2	1	3	0	3	0	1	17	1	5	120
	physiological	Circulatory	4	1	0	0	0	1	2	0	12	2	4	2	0	0	4	0	3	3	0	1	39
		Metabolic	7	0	0	0	0	0	1	0	18	3	6	2	0	0	7	0	2	11	0	2	59
		Biomechanical	21	1	12	0	0	6	5	0	31	9	7	6	1	1	5	0	0	29	0	3	137
		Neuromuscular	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	behavioral	Psychological	1	0	0	0	1	0	1	0	2	1	1	0	1	0	0	0	0	2	0	1	11
		Psychophysical	14	0	6	0	0	1	3	0	19	2	8	0	1	0	1	0	1	6	0	0	62
		Sociological	1	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	4
		Totals	77	3	23	3	11	15	49	0	115	26	29	11	8	1	20	0	8	72	2	15	488

Figure 2. Literature summary tabulation.

Research Needs Related to Hazard Indices

Future studies of the hazard indices associated with MMH should:

1. Use a standardized classification scheme for injury/illness statistics (e.g., Z16.1 or OSHA System).

2. Examine the relationships of parameters which best reflect human and tissue tolerance to a physical stress (e.g., pleural and cardiac tissue rupture levels, EKG, angina, arrythmias, elevated recovery pulse rates, and blood pressures and hyperventilation, etc.) with physiological and mechanical fatigue.

3. Document the appropriate aerobic capacities of workers involved in MMH jobs to establish tolerance and fatigue states based on the metabolic rates and muscle functions required by these activities. Further, measurement of the concomitant body core and muscle temperatures are needed.

4. Develop more comprehensive biomechanical model predictions of the complex mechanical stresses imparted to the various body tissues during MMH. Such models should also be used to interpret experimental findings (e.g., EMG levels, tissue force and pressure measurements, radiographic alterations, etc.) as well as to be validated by such parameters. Further, better techniques should be developed for evaluating kinesiological and postural changes in workers. Methods for collecting and using cadaver data to determine their mechanical properties must also be adapted to the occupational trauma situation.

5. Determine how well a person can perceive his or her own maximum capacity to sustain a physical effort. Since psychophysically based human performance limitations can and are providing useful guidelines for the specification of MMH tasks of many kinds, research should be instigated to define the testing conditions which could significantly affect results. Also, larger and more heterogeneous working populations should be studied under a variety of conditions to determine their psychophysical tolerance to MMH.

Research Needs Related to System Characteristics

Future studies of the hazards associated with the job system characteristics in MMH need to consider the following:

1. **Worker Characteristics.** Future studies are needed to:

a. Examine the fundamental worker physical characteristics between and within sexes (e.g., strength, body mass, postures, anthropometry). Controlled laboratory and field studies of job stresses are needed for different worker age groups. Body weight, as a variable, needs to be studied in conjunction with other anthropologic and motor characteristics (e.g., stature, strength, mobility, reach, lean muscle mass, ponderal index, etc.).

b. Examine the role of the depth perception of a worker interfacing with material as well as the role of visual adaptation in hazards associated with poorly illuminated work areas. Since angular acuity is often corrected in gross material handling, it probably would not be a factor in assigning risk. The use of multifocal corrective glasses, however, may be a factor, and further research is needed. Contrast and dynamic visual acuity are also important sensory capabilities that are expected to affect handling performance and warrant additional study in this context. The tactile (cutaneous) senses may also be important to the worker handling slippery, hot, or cold objects. The proprioceptive senses may be important to the material handler of unstable loads which require an awkward body posture. Further, kinesthetic abilities (awareness of position and movement of body parts) may affect material handling capabilities as may the vestibular orientation mechanisms related to body balance. Each of these sensory process capabilities may play important roles in materials handling illnesses and injuries and thus warrant careful delineation and study in the context of the hazards of MMH.

c. Strive to provide a more comprehensive characterization of the role of the motor capabilities of the working population to include:

   - strength in postures other than the sagittal plane,
   - endurance capabilities, including localized, whole body, and sporadic endurance,
   - range of movement capabilities,
   - kinematic capabilities, and
   - muscle training state.

   As data are made available from the above research, the focus of study should turn to the development of methods for using motor capabilities (in particular, strength data) more effectively in task design. It is also recommended that how worker motor capabilities relate to hazard indices other than biomechanical and psychophysical (e.g., metabolic, circulatory/pulmonary, and psychological) be studied.

d. Develop functional tests for evaluating lower back injury to be used in well-controlled laboratory and field studies.

2. **Material/Container Characteristics.** Future studies are needed to:

a. Recognize that object weight is neither an additive variable, nor is it a simple linear component. Care must be exercised in future research to assure that this nonadditivity and nonlinearity is taken into consideration. The concept of the "load moment" as an indicator of stress has not been used enough in previous investigations, and thus, it is recommended that its use be emphasized in future research. The majority of studies in the past have recorded only "lifting" of objects in the sagittal plane. If the true characteristics of load are to be understood, more extensive study of "twisting" and "turning," "pushing," and "pulling" activities is needed. Also, the moments of other body members may be used to characterize risk in terms of the kinetic chain of moments and certainly warrant future study. Further, it is expected that some loads are hazardous due to inadequate labeling. The ability of the materials handler to perceive load characteristics of weight and force is no doubt minimal for the nonrepetitive handler. Hence, guidelines need to be developed regarding the labeling of objects for hazard due to weight and other container characteristics.

b. Characterize better those shape parameters that may be standardized in measurement for use in hazard evaluation. Specifically, research is needed on the effects of frontal plane width and object height as they relate to risk.

c. Characterize the general problem of one-handed material handling. This, coupled with a better characterization of the postures encouraged and stresses induced by asymmetric load distributions, would fill a gap in knowledge which has been long overlooked.

d. Investigate the proper design and placement of coupling devices. The criteria for including handles, the difference in capacity to carry loads, and the user acceptance of alternative coupling devices require research attention. Research is needed to determine the characteristics of good coupling devices, including for example, surface texture, placement, orientation, dimension (including bearing surface). Also, handles may affect postures and, thus, induce additional materials handling hazards so there is a need to discriminate between lifting, carrying, pushing, and pulling-type coupling devices. Adequate literature relating grip strength and basic hand dimensions to the hazards of MMH (both gloved and ungloved) is lacking. Before viable safety criteria for coupling devices can be established, these data must be obtained.

3. **Task Characteristics.** Future studies are needed to:

a. Examine the sequencing of lifting patterns encouraged by workplace layout and the role of confined spaces on the hazards of MMH. Study is needed to understand the role of imperfect surfaces (e.g., stairs, grades, and slippery surfaces) on hazards, including the worker's perception of imperfect surfaces. Further the characteristics of good coupling and uncoupling points need to be understood. Included here is a need for studies of the effects of movement distance, direction and extent of path, obstacles, and nature of the material destination. The hazards associated with MMH while in a seated position require study. Here, too, research is needed to determine criteria for seated workplace design to include the effectiveness of footrests and general chair configuration.

b. Carefully delineate the role of periodicity of efforts. For example, often a load may be lifted 20 times per day with an average lift duration of 2 seconds per lift for 2 weeks every other month with no lifting at other times. The quantification of the influence of frequency and duration on hazard potential is not easily delineated. Frequency, duration, and pace have historically been viewed only with mean (average) values; however, attention to the variability of these measures by spectral analysis would be desirable. The possible interaction of these variables with the material/container characteristics, namely load, also merits attention. The effects of overtime (increased task duration) on the hazards to the individual involved in MMH require additional study. The significance of self-paced versus machine-paced operations in terms of hazard potential warrants research attention.

c. Identify the effects of those physical environmental variables that represent compounded stress and hazard to the worker including, in particular, temperature and altitude.

4. **Work Practices.** Future studies are needed to:

a. Determine common lifting postures through field evaluations in industry. Unfortunately, the degree or nature of the hazard due to posture dynamics is not well described in the literature, and hence both laboratory and field studies are warranted.

b. Determine the effectiveness of different, well-defined selection and placement policies.

c. Develop and evaluate criteria for predicting the rest requirements in MMH jobs based on several of the hazard indices. In this same regard, research is needed to determine if productivity incentive systems modify hazard potential in MMH jobs.

These last two recommendations will require further methodological developments before the full benefit of the work can be realized.

If the hazards of MMH are to be effectively reduced in the future, there is a need to go beyond these single factor studies of the problem to include the interactive influence of multiple factors. In general,

1. Research is needed on the interaction of the various system characteristics (the worker, the material/container, the task, and the work practices) as they collectively influence the hazards of handling.

2. Studies must also reflect the multiplicity of hazards associated with MMH, including not only injuries and illnesses, but the physiological and behavioral indices as well. To this end, multivariate statistical analysis techniques must be more conscientiously and consistently applied.

3. More careful elaboration and application of sound statistical measures and techniques are required to characterize hazard and to provide measures which are reliable and reproducible. Further, the use of critical incidence techniques and nonparametric statistical methods has not received enough attention in previous studies; their use in the future should be better documented.

4. To address the multiple dimensions of the hazards of MMH, it is recommended that deliberate programs be developed that bring to bear more subspecialties of expertise. For example, medical

professionals should be encouraged to work together with engineers and research scientists to develop programs which incorporate each specialty in the design and implementation of safe, healthy systems.

5. Finally, there is a recognized lack of standardization of methods and measurements. To some degree this must be accepted. The important point is that these measurements and methods must be documented better in reports so that others may benefit from developments in the area and so that adequate verification and validation are possible.

EXPERIENCE WITH THE EPIDEMIOLOGICAL APPROACH

Due to the multiplicity of hazards and systems components associated with these hazards in MMH, the integration of information becomes a major concern. Over the past 8 years, a number of epidemiological studies performed at the University of Michigan point out the need for an occupational health monitoring and evaluation system (OHMES). Because of the dynamic nature of jobs and employees, such an integrated system was developed (Herrin et al., 1976) to document and report system characteristics and medical consequences.

The breadth of documentation requires the cooperative efforts of interdisciplinary teams in engineering, medical, personnel, and line supervision functions. Collectively, these four sources of information within plants must be coordinated as shown in Figure 3.

The first source of information, the industrial engineering function, provides detailed job evaluations for each materials handling job to which employees are assigned. Objective data about the particular job requirements, e.g., the size and weight of the objects to be lifted, the distance (horizontal and vertical) of necessary lifting, etc., are documented.

The three other information sources are relied upon as each employee passes through the various stages of his/her work experience. First, personal health evaluations are completed by medical hygienists as prospective employees are assigned to materials handling jobs (whether as an initial assignment or a transfer). Data about job-related strength tests (Chaffin and Herrin, 1976) of the employee, medical history, and the doctor's prognosis of the physical capability are documented. Supervisor evaluations are performed for each employee early in their tenure on a particular job, and again in the event the employee terminates his

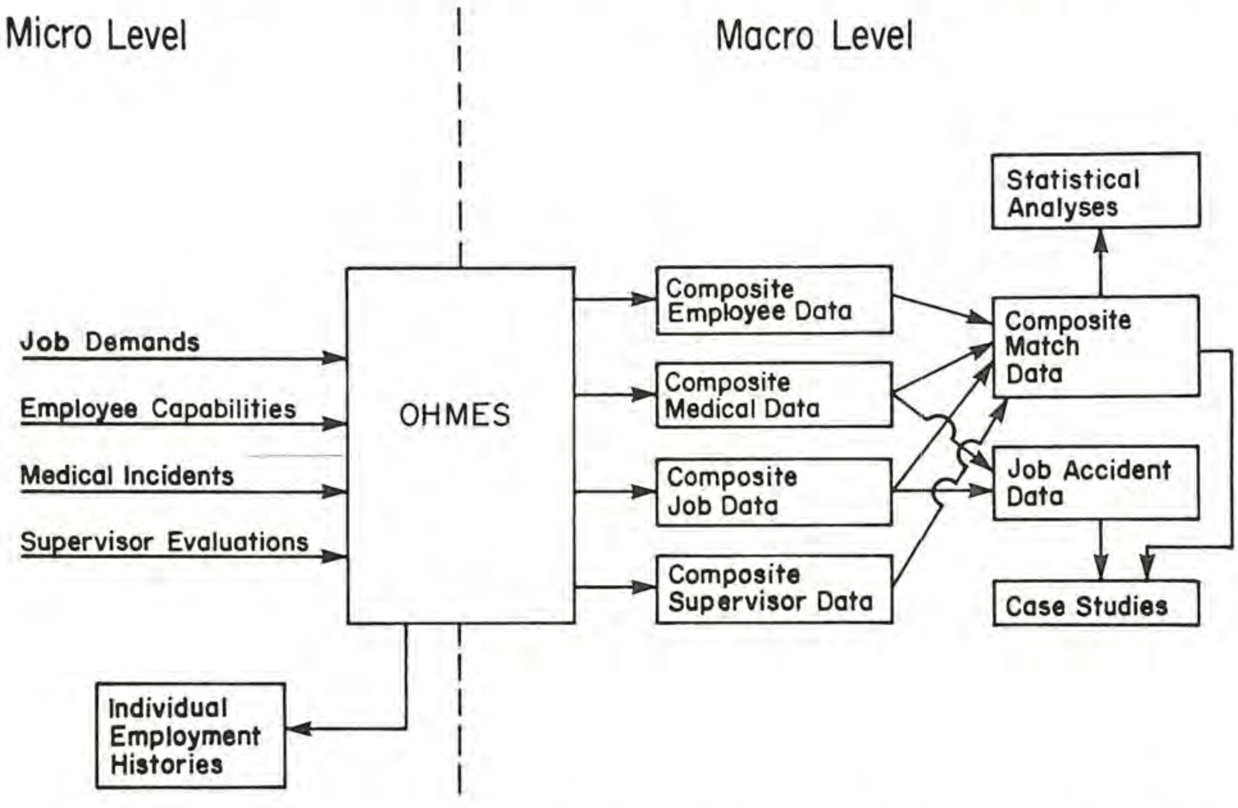

Figure 3. Reporting in the occupational health monitoring and evaluation system (OHMES).

work on a particular job. The supervisor reports on the employee's performance attributes in the assignment.

The employee medical records provide details for each injury or illness case. This report by the medical staff includes the nature of the disruptive incident, the type of complaint, diagnosis, treatment, and the number of days lost or number of days on work restriction.

THE MEDICAL CONSEQUENCES OF WORKER/JOB MISMATCH

One index that has been related to low back pain in industry is the Lift Strength Rating (LSR) of the job, which is defined as:

$$\text{LSR} = \frac{\text{Load lifted (max)}}{\text{Predicted maximum lift capability*}}$$

This index approaches 1.0 as the job becomes more stressful (i.e., only 2.5% of the industrial male workers are capable of doing the job).

In a pilot study in five plants of a large manufacturing company, 38 jobs involving 135 people were evaluated to determine their LSR's. Over the 5-month study, the incidence rates of low back pain were tabulated (Figure 5).

*Predicted value shown in Figure 4.

Two conclusions were drawn from this initial study. First, jobs having high LSR values were associated with significantly higher incidence rates of low back pain. Second, the incidence rates were higher than expected for the high LSR jobs when compared with values quoted by medical and safety personnel. Because of these trends and magnitudes, the study scope was broadened.

A total of 411 employees (males and females) working on 103 jobs were monitored in terms of medical incidence experience for approximately 1 year; in 17,430 man-weeks exposure, 25 incidents of low back pain were documented. Only those incidents identified by the employees as job related are plotted in Figure 6. The important points to note are (1) that the trends of low back pain incidence are consistent with the earlier study whereas (2) the magnitudes are sharply reduced. This latter observation is believed to be a result of the exclusion of off-the-job incidents.

The results of this study were believed to confirm, in a specific fashion, the inclinations of many medical practitioners. It was concluded that the lifting of loads in positions that create an LSR of 0.2 or greater should be considered potentially hazardous to "some" people.

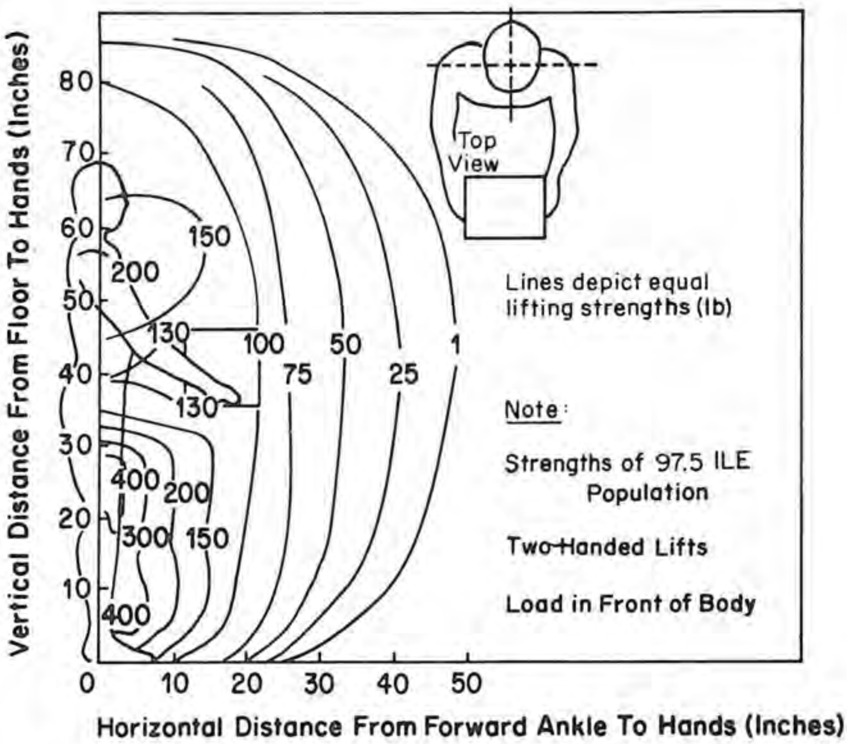

Figure 4. Predicted listing; strength of large, strong male (Chaffin and Park, 1973).

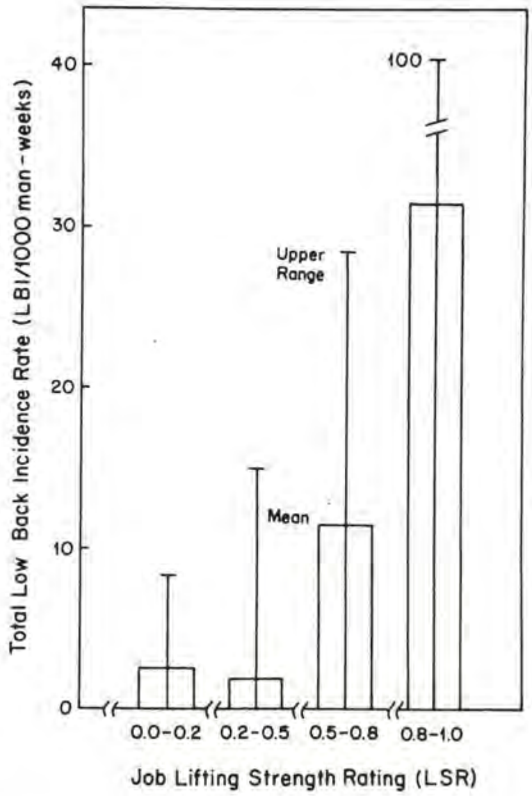

Figure 5. Low back incidence (not necessarily suffered on the job) per man-week in study for jobs having various lifting strength requirements (Chaffin and Park, 1973).

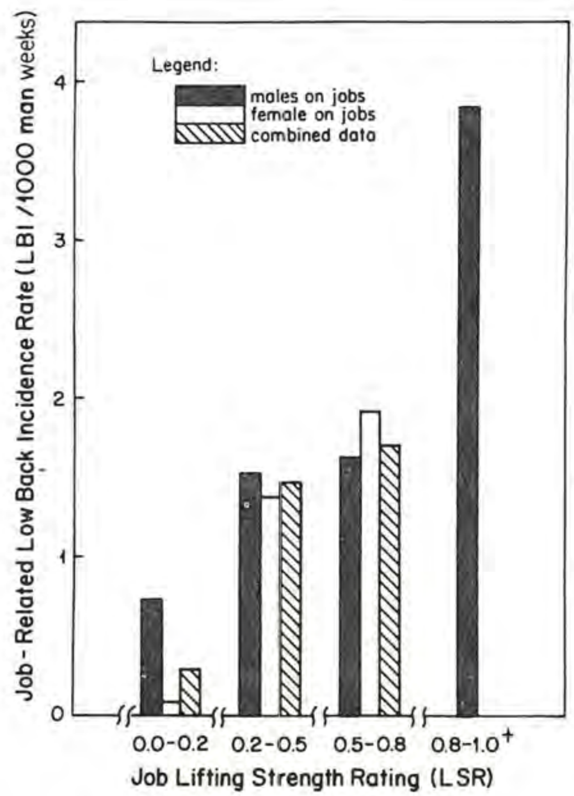

Figure 6. Mean low back incidence rates for jobs having various lifting strength requirements (Chaffin and Park, 1973).

It appeared from strength testing of the 411 employees in the second study that those who demonstrated they could produce at least as much lifting capability in a standardized isometric test as was required to lift objects on the job had approximately one-third the incidence rate of low back pain as those not able to demonstrate such high lifting strength. This result led to the most recent study which involved evaluating over 900 jobs and 551 employees in six industrial plants. As people were transferred or hired into these jobs, their strengths were assessed by standardized strength tests as well as in the LSR posture. These latter strength assessments require knowledge of the most stressful job element(s) so that the isometric job position strengths can be simulated in the medical departments before actual placement.

Table 3 illustrates the medical experiences over a 2-year period for these 551 employees. It is noted that although the incidence rates for back injuries were not strictly increasing with object weight handled there are very strong trends in the medical treatments (reflected in days lost and/or days restricted) administered by plant physicians. It is also interesting to note the possible extension of these trends to medical consequences other than back pain such as general musculoskeletal, contact (cuts and abrasions), and nonspecific (headaches, intestinal disorders, etc.) complaints.

CONCLUSION

The taxonomy of knowledge related to the hazards of MMH continues to expand with improved measurement and analysis technologies. These methodologies need to be integrated into the routine operations of researchers and practitioners alike. More comprehensive data are needed to characterize each of the job system characteristics: workers, tasks, material/containers, and work practices. These data must be carefully measured, documented, and evaluated so that adequate models and generalizations can be drawn. This integration of more and more comprehensive information is facilitated by a systems approach (OHMES) to monitoring these processes over time. Such comprehensive, evaluative field studies of corrective actions and controls are prerequisites to the future minimization of the hazards of MMH.

Table 3. Medical experience on multiple employee jobs (Chaffin et al., 1976).

Maximum object weight (lb)	*Total medical*	*Nonspecific complaints*	*Contact injuries*	*Musculo-skeletal injuries*	*Back injuries*	*No. jobs*	*Response (per million man-hours)*
<50	602	213	235	119	35	16	
50-80	855	265	408	76	106	40	Incidents
>80	668	217	285	97	69	22	
<50	371	371	—	—	—	16	
50-80	1111	826	—	23	262	40	Days lost
>80	2940	1334	—	188	1418	22	
<50	157	—	22	126	9	16	
50-80	1926	567	363	649	347	40	Days
>80	2788	123	233	1075	1357	22	restricted
<50	528	371	22	126	9	16	Days lost
50-80	3037	1393	363	672	609	40	+ days
>80	5728	1457	233	1263	2775	22	restricted

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CHAPTER 1. SUMMARY

Dr. Dukes-Dobos is well placed to expound and develop NIOSH's interest in manual materials handling safety. The themes he introduces here are orchestrated in subsequent papers — Is there any point in looking for the "one best method" of lifting? How can legislative bodies help reduce injury and increase productivity? Will we ever know enough to set "fair" standards?

The first specific recommendations come in Herrin's paper where a definite relationship is shown between injuries and the ratio of task demands to worker strength. The original report by Chaffin, Herrin, Keyserling, and Foulke (1976) needs to be read for a full appreciation of the findings; but even on the evidence presented here, the case for individual job/worker matching is very strong. In these times when such legislation as the Equal Employment Opportunities Act has caused many companies to shy away from selection and placement, it is appropriate to remember that it is one available strategy. As Ayoub and El-Bassoussi show in a later paper, it is specific muscular strength that governs lifting ability rather than general strength measures or even age or sex.

There are many questions raised in these opening statements; the rest of this volume hopefully provides a few of the answers.

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Chaffin, D. B., Herrin, G. D., Keyserling, W. M., and .Foulke, J. A. 1976. Preemployment Strength Testing in Selecting Workers for Materials Handling Jobs. DHEW (NIOSH) Publication No. 77-163.

CHAPTER 2

MEASUREMENTS AND STANDARDS

INTRODUCTION

In the previous Chapter, Herrin summarized a taxonomy of hazard indicies in manual materials handling. These are all effects of the task on one or more parts of the human organism. If we are to understand the literature on manual materials handling and if we are to look towards future needs, the bodily subsystems affected by these tasks need detailed consideration. Were manual materials handling tasks all limited by one factor, such as spinal stress, then standard setting and prescriptive design would be much simplified. In reality, we are faced with a set of potentially limiting subsystems for each of which, if specific task demands exceed individual worker capabilities, a limitation on either performance or safety will occur.

The typical effect reported in the literature is low back pain from lifting, although this is only now being measured with any epidemiological rigor. In this Chapter, three levels of measurement of low back trouble are represented. Firstly (Troup's review of the back injury problem), its clinical diagnosis and reporting show that neither the detection of back injuries nor the determination of their causal factors are areas where we can proceed with certainty. One form of back injury is damage to the intervertebral discs so that measures of the stresses on and in these discs can be a real aid to classifying task damage potential. Andersson, Örtengren, and Nachemson review their studies of direct disc stress measurements, and Davis and Stubbs measure a parameter that has been shown to be closely correlated with disc stress — intra-abdominal pressure.

Still within the mechanical aspects of the muscular/skeletal system, the second limitation to be considered is obviously the strength of individual muscles. Kroemer, in his paper on strength measurement and testing, points out that the task demands a torque about a joint rather than just a force. His paper is extended by Drury and Spitz to cover strength limitations in extended muscular contractions rather than short duration (explosive) demands.

The papers thus far have considered the limitations of subsystems directly stressed by the manual materials handling task. But central systems are also stressed, in particular the energy production subsystem and the cardiovascular system. Rogers shows how energy production can be limited by the ability of the body to absorb oxygen and how this can pose a practical limitation on task performance. Lind and Petrofsky review their work (and that of others) on cardiovascular stresses induced by manual materials handling tasks.

Finally, the human being engaged in these tasks is a conscious entity who can estimate the stresses on his body and his own willingness to tolerate them. Snook, who pioneered in psychophysical methodology, presents this as one of the most reliable methodologies and one that is in substantial agreement with other more direct measures of hazard.

MANUAL MATERIALS HANDLING — THE MEDICAL PROBLEM

J. D. G. Troup

INTRODUCTION

When a medical practitioner is concerned with a whole working population, he must look at the effect of their work on their health and at the effect of the individual's health on fitness for work. Though he may be involved in treating workers for the injuries and diseases that arise during work, their consequent rehabilitation, and the proper placement of the disabled worker, his primary duty is to prevention. Success depends on his ability to recognize the short- and long-term hazards to workers' health. Once recognized, the hazard — if it cannot be done away with — should be brought down to acceptable levels; those most susceptible to it should be removed from exposure; and, to the extent that the hazard may be physically uncontrollable, workers should be trained to keep out of trouble. Of the two, the short-term hazard is much the easier to contend with. The long-term ill effects of work on health may be more difficult to identify, and the evidence needed to define the levels to which workers can safely be exposed is often sketchy.

Uncertainty dominates the medical aspects of materials handling accidents. The identification of their causes and their prevention, the limitation of handling stresses to avoid chronic ill effects, and the methods for assessing individual capacity for work are all made difficult, if not impossible, by lack of factual knowledge and practical techniques.

Little is known about the long-term effects of materials handling. Degenerative joint disease was found to be commoner in those exposed to heavy manual work but the data, which were collected in studies in Sweden and in the North of England a generation ago, may no longer apply (Hult, 1954; Kellgren and Lawrence, 1958). In the short-term, however, handling has long been recognized as a cause of injury at work, particularly in those industries in which it is, or has been, intensive (Jackson, 1968). In many of these cases, the injury is pathologically determinable, and if good witnesses exist, the biomechanics of the accident will emerge. Then the purely physical approach to prevention offers no particular problem. Yet, it is well to appreciate that in a very large number of accidents at work, the resulting injury may be a psychological solution to some preexisting stress of social or emotional origin (Hirschfeld and Behan, 1963). Not surprisingly, a substantial number of handling accidents lead to an injury that is imprecise in nature, and it becomes doubtful if there really had been an accident.

Unspecific strains and sprains account for a third or more of reported factory accidents, and the bulk of them affect the spine and trunk. This group represents a major problem because, unlike a cut finger or a broken toe that provides direct evidence about the accident, the cause is obscure and the diagnosis difficult. Even in those cases in which an unexpected event disrupts the normal pattern of a handling task (in other words, a truly accidental happening in contrast to the large number of injuries in which symptoms begin suddenly while the victims are doing what they usually do), the history of injury is of limited clinical value. There are no facts that relate the mechanics of the accident to the location in the spine of the inflammation resulting from the supposed trauma. Clinical experience might suggest that the very first back injury sustained is often truly accidental and that that is less likely to be true of later episodes. But this is of minor diagnostic value, and it is to be doubted if there is anything in the purely clinical experience of back injuries that can be applied to prevention. It is also as well to bear in mind that clinically no real effort is made to diagnose the cause of pain or locate the site of origin of symptoms in the ordinary run of strains and back injuries unless symptoms prove intractable. Only after the conservative approach is seen to have failed do the real diagnostic investigations begin. They are too expensive and time consuming to be worth tackling so long as there is reasonable hope of a natural remission.

BACK INJURIES

Definition

"Back injuries" present a semantic problem because, epidemiologically, it is not possible to give the words a practical definition. In some industries, 90% of all episodes of back pain are reported as accidents at work (Troup, Roantree, and Archibald, 1970), whereas in the population as a whole, attacks of back pain are attributed to physical activities in only 30% to 50% of the episodes (Ward, Knowelden, and Sharrard, 1968; Magora, 1974). This reflects not so much the financial advantage of reporting an accident as the frequency and heaviness of manual work in different jobs. It may be expedient epidemiologically to lump all spells of back pain together without consideration of injury as such (Chaffin and Park, 1973; Chaffin, 1974). Alternatively, it may be justifiable to classify the back pain according to whether the subject considers that it originates at work (Zuidema, 1973) though inevitably this leads to the inclusion of cases in which spells of back pain arise from postural stress (Walford, 1960; Magora, 1974; Kelsey and Hardy, 1975; Corlett and Bishop, 1976). Back injuries are not readily definable, and it is often unproductive to try.

Experimental Work

The mechanism of injury can be studied by investigating the physical properties of the tissues of the body and recording their mechanical behaviour under load. Ruptures of disc, ligament, and muscle; fractures of the vertebral end plates and body; and fractures of parts of the vertebral arch including the articular facets have all been demonstrated. Unhappily, it is rather difficult to be sure that the forces applied to the specimens are biologically relevant. It is not at all easy, for example, to reproduce experimentally a clinically recognizable fracture. The crack either starts in the wrong place or propagates in the wrong direction—not surprisingly considering the sophistication of laboratory conditions and the fact that specimens are usually stripped of muscle and ligament in order to embed them in a testing rig for the application of controllable forces. Extrapolation from the results of cadaveric studies to the clinical situation is therefore unwise; in addition, tissues behave quite differently under load when degenerative changes have set in and, clinically, these changes are impossible to detect in the early stages.

Another reason for caution is that the temporal pattern of normal handling activities seems to differ widely from the strain rates applied in these studies. The strength of musculoskeletal tissues is dependent not only on strain rate but on the duration of applied stress; and on such factors as prestress conditions, including "vibro-creep" (Perey, 1957; Kazarian, 1972, 1975). If the spine is subjected to stress long enough for creep effects to obtain, it stiffens and its capacity to resist without failure is reduced. If the strain rate and the jerk are high enough, there may be too little time for energy to be dissipated.

Comment

Because of the difficulty of defining back injuries satisfactorily in pathomechanical or epidemiological terms, one is driven to considering the evidence concerning the accident itself and any other factors predisposing the individual to the onset of symptoms. Regrettably, this evidence is less than reliable. Descriptions in the accident book and the reports of the safety engineer are brief and amount to little more than labels of convenience. Of even less value is the medical note. Even if the doctor does ask about the patient's job, he seldom inquires much into the physical work load involved; often he fails to record the data that have been elicited. Statistics from official sources and retrospective reviews of handling injuries and strains either from industrial or hospital records are, therefore, a waste of time.

Clinical experience, for the time being, is all there is to go on. Though plainly subjective, it suggests that there is a relatively safer zone between the high strain rate, such as the effects of a fall, and the low strain rate combined with sustained effort, as when someone becomes stuck with a load that proves to be too heavy. They are utterly different in terms of the time/course of spinal stress and its effects. Both, however, come into the category of the unexpected and are typical of the reported causes of back injury (Troup, Roantree, and Archibald, 1970; Magora, 1974). In guessing just where a safe temporal zone for handling lies, the purely physical aspects of lifting have to be taken into account, particularly the argument that "the important ingredient of a successful lift is an explosive effort as early as possible" (Grieve, 1970). Perhaps 100 msec to 300 msec is long enough when handling a subjectively heavy load; and anything over 500 msec could be dangerous.

Clinical experience also suggests that susceptibility to the strains and sprains of handling injuries increases with the duration of preceding postural stress and with the frequency and magnitude of dynamic stress prior to the onset of pain. Just as there are changes in the function of a muscle caused by its preceding activity, work itself appears to affect the capacity of the spine to withstand stress and dissipate energy; this leads to diurnal variations in handling ability that are comparable to the diurnal variations in the threshold of pain sensation and not unrelated to them.

STRATEGY FOR RESEARCH

Codes of standards for safe handling are needed by the ergonomist for the design of work, by the safety instructor for training, and by the medical officer to identify the accident prone and to assess working capacity. For the time being, their approaches must remain empirical for they are faced with a basic ignorance of the nature of many of the injuries and strains they seek to prevent. There is a particular need to distinguish between the true accident and the chronic working or postural stress for which there may be an ergonomic solution. For example:

- with the sudden onset of pain during handling work, in what proportion was there a truly unexpected disturbance of the normal pattern of work and in what proportion was it only the pain that was unexpected?
- between these two groups, is there a difference in the ratings for chronic stress at work?
- does the previous experience of a true handling accident predispose to further injuries and symptoms of mechanical stress at work?

The answers to these questions will come mainly from prospective epidemiological surveys; and the problem is not so much in the design of the questions as in finding the environment in which reliable answers can be found.

The second problem is the want of facts concerning the time/course of stress transmitted by the body during manual work. What is needed is a series of studies to give an "order of magnitude" to the rates of increase, the peaks, and the durations of stress arising from handling activities and working postures. The aim should be to gain insight into the typical behavioral aspects of spinal dynamics, starting with those jobs in which handling accidents and postural stress are most prevalent. This would provide the bioengineer with the data needed for the "input" in investigations into the dynamic characteristics of the tissues of the spine and trunk. The apparatus used in bioengineering studies of osteoligamentous preparations, and for applying forces to any system, are already sufficiently elegant, and there are no problems apart from cost. Measurements obtained from the living human are another matter. Direct measurements of tissue stress are ethically impossible for the most part even if they are technically feasible; and with any transducer applied to the body surface, there is a problem of stability, which is not always soluble. At present the most valuable techniques, biomechanically and physiologically, depend on indirect measurements.

TECHNIQUES FOR RESEARCH

Force Measurements

Given data on the mass of loads handled and their acceleration, the forces applied manually can be calculated (Grieve and Arnott, 1970). Similarly, the use of a force platform (Whitney, 1958; Konz, Dey, and Bennett, 1973) gives measurements of the reaction to body movement and external work. In combination, calculating forces applied manually and using a force platform allow the use of a simple model consisting of upper and lower force elements acting about the centre of body mass; but more elegant techniques have still to be developed if the time/course of stress is to be analyzed at any one site—say, the lumbosacral joint. Nevertheless, by measuring the force at the feet and hands together with the lift impedance (the force at the feet minus body weight divided by velocity of the load) during a manual task, it is possible to calculate the velocity of the center of body mass and of the load, the momentum acquired by the body, and the rates of work produced by the upper and lower force element. By these means, major variations in the time/course of stress are demonstrable between lifting techniques and between the magnitude of loads (Grieve, 1974; Troup, 1977). Using simply a vertical force plate and a load accelerometer, lifting actions can be studied in the field (Hawkins, 1972).

Physiological Measurements

Intra-abdominal Pressure

Increases in intra-abdominal pressure are related to the magnitude of loads handled and to the speed of handling them (Davis, 1956, 1959; Bartelink, 1957; Morris, Lucas, and Bresler, 1961; Davis and Troup, 1964, 1966a) and to the torque developed by the trunk during the application of sustained forces (Davis, Whitney, Troup, and Gear, 1965). The measurements are sensitive enough for accurate assessment of the rate of increase in pressure (Davis and Jackson, 1962). Any transient pressure changes, due for example, to peristalsis, are easy to recognize. Thus, the measurements play a useful role in mapping out the pattern of spinal stress and are applicable to field studies (Stubbs and Davis, 1973).

Some reservations, though, should be kept in mind. There appears to be a reciprocal activity of the muscles of the trunk controlling intratruncal pressures and those of the erector spinae group. As an aid to spinal extension, increases in intra-abdominal pressure have a mechanical advantage in the early stages of the lift when the lumbar spine is flexed and the back muscles stretched, and vice versa (Davis and Troup, 1965). Further, any concomitant activity in rectus abdominis muscle during increases in intra-abdominal pressure (when pushing, for example) will prevent lumbar extension. Finally, it can be noted that the pressure increases normally consist of brief peaks, and that during isometric truncal stress, the pressure falls to a plateau which varies with the respiratory cycle.

Electromyography (EMG)

EMG has only a limited role to play; it is confined to demonstrating the occurrence and frequency of myopotentials and the duration of the resulting interference pattern. The electrical activity varies logarithmically with the distance between muscle fibre and electrode; recording conditions are thus altered by movement. Very large numbers of electrodes may be needed to monitor the activity of all the muscles of a group. EMG gives no information about the passive component of muscle tension—this would have to be computed from data on muscle length and its rate of change—nor does it reveal anything of the mechanical state of the contractile element of the fibres. The frequency characteristics as well as the total electrical activity from a given muscle varies with its length and with time and the symptoms of fatigue (Kadefors, Kaiser, and Petersen, 1968; Troup and Chapman, 1972a, 1972b; Chaffin, 1973; Grieve and Pheasant, 1976). By itself, EMG gives only a tenuous guide to truncal or spinal stress.

Energy Expenditure

Measurements of energy expenditure are applicable to studies of repetitive manual work rather than to the isolated task. They are usually made by collecting expired air in a bag and calculating the oxygen uptake from inspired air per unit time. Originally, measurements were made to determine the industrial workload for women (Cathcart, Bedale, Blair, MacLeod, and Weatherhead, 1927). Since then they have been used to distinguish between lifting methods (Das, 1951; Stubbs and Davis, 1973) and to determine reasonable rates of work (Numajiri, 1964; Jorgensen and Poulsen, 1974). Heart rate, too, has been used to distinguish the relative costs of lifting methods (Davis and Arnott, 1966).

With the mechanical efficiency of muscular work varying widely about a modest mean, it could be best not to rely upon a single measure of energy expenditure, particularly as most manual work makes both postural and dynamic demands. Heart rate, blood pressure, peripheral blood flow, and cardiac output are all relevant factors in distinguishing the effects of static and dynamic muscular activity (Lind, Taylor, Humphreys, Kennelly, and Donald, 1964; Lind and McNicol, 1968). Likewise cardiac output is a relevant factor when considering metabolic changes and respiratory gas exchange during work (Davies, di Prampero, and Cerretelli, 1972). One other set of factors must be accounted for in all assessments of the energy expenditure of manual work—the effects of postural change on circulation (Hamilton and Morgan, 1932; Brotmacher, 1957) and (together with the splinting effects of the shoulder and abdominal muscles on the rib-cage) on lung compliance (Lim and Luft, 1959) and ventilatory capacity (Davis and Troup, 1966b).

Strength Measurements

Innumerable studies have been made of lifting, pulling, and pushing strength. Mostly the exertions have been static, or as nearly so as possible. They have been made to determine the effect of posture on maximal strength (Vernon, 1924; Whitney, 1958; Troup and Chapman, 1969) and, of special relevance, to establish the relationships between individual strength, the physical demands at work, and the incidence of back pain (Chaffin, 1974). The maximal strength exerted isometrically is partly a physiological function based on the number and transverse cross-sectional area of muscle fibers and the intensity of motor neurone discharge, and also an individual tolerance for pain. Dynamic strength, not in terms of maximal effort for a single exertion but the maximal comfortable load for repeated work, has been assessed, and the results have proved consistent (Snook, Irvine, and Bass, 1970; Snook and Ciriello, 1974).

The dynamic characteristics of strength in terms of the capacity to transfer energy from the body to the load to be handled has had little or no attention.

SAFE HANDLING TECHNIQUES

The current teaching in training for safe handling is that the body should be given kinetic energy that can be transferred to the load, and, likewise, that the load can be given horizontal movement that can be translated into vertical movement. When successfully taught, these techniques feel easier, and the question is whether they are safer. In general, we can accept that when workers are given an adequate margin between physical work load and individual strength, and when the sense of effort is removed from their labours, episodes of back pain become less prevalent (Chaffin and Park, 1973; Chaffin, 1974). One of the features of successful handling, however, is timing. But when workers are trained to do a given job so that it feels easier:

- is the total spinal stress reduced?
- and if so, how?

- or is it just a trick to get more work for the same amount of stress and perhaps increase the long term risks?

In a purely physical sense, it is a good thing to limit the duration of effort and so reduce the risks of creep effects. The possible disadvantage is that there may be too little time for the threshold of sensation of undue effort to be reached. Injuring healthy tissues is not necessarily painful at the time of injury, and accidents arise from the unexpected situation that gives no time to react physiologically and avoid the danger. Falls while handling are commonly reported (Troup, 1965; Troup, Roantree, and Archibald, 1970; Manning, 1971), and if skill and coordination in timing is to be a feature of training, it is paramount that we also teach how to avoid the unexpected and how to cope with handling emergencies when they arise.

CONCLUSIONS

In the present state of knowledge, it is probably acceptable to impose standards based on subjective estimates of load-handling capacity, graded according to the distance between the center of the load mass and the body (Snook, rvine, and Bass, 1970; Snook and Ciriello, 1974; Kramos, 1975). Yet it would be wrong to think of these as other than temporary expedients. It is just as important to say how the load should be handled—once we know the answer. Even with loads within the recommended maxima, major differences in the temporal pattern of stress are readily demonstrable (Grieve, 1974; Troup, 1977).

The basic need for research concerns the pathomechanics of the injuries and strains of manual work; and the predisposing factors that obtain before the injury or onset of symptoms, whether they are social, psychological, or just the mechanical effects of the preceding postural and dynamic stresses. At present we do not know enough about what we are trying to prevent. Collaboration between the disciplines is a necessity: the safety officer adopting more reliable methods of reporting, likewise the clinician; the bioengineer and the physiologist cooperating in the design of studies of the dynamic response characteristics of the spine and trunk; and the whole team collaborating in the development of tests of working capacity that can be applied in industrial training, in preemployment examination, and in rehabilitation.

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STUDIES OF BACK LOADS IN FIXED SPINAL POSTURES AND IN LIFTING

G. B. J. Andersson, R. Örtengren, and A. Nachemson

INTRODUCTION

The need for continued research into the relationship between low back pain and manual materials handling has been outlined elsewhere in this volume. Knowledge about the stresses on different spinal structures during work is useful not only to design workplaces and work procedures, but also to investigate this relationship epidemiologically. Difficulties at present in obtaining direct measurement data at the worksite necessitate simulated laboratory experiments and analytical approaches.

This paper is a summary and synthesis of a series of laboratory experiments (Andersson et al., 1976a, 1976b, 1977a, 1977b). The aims of these studies have been threefold: to obtain knowledge about the magnitude of low back stress under standardized conditions of loading, to evaluate and compare different methods used to measure these stresses, and to achieve the necessary experience to conduct further studies on the factory floor.

MATERIAL

Three different groups of healthy volunteers participated in the investigations. Each of these groups has been described in detail in the paper in which the result was first reported (Andersson et al., 1976a, 1976b, 1977a, 1977b). The age range was from 23 to 35 yr, heights between 169 and 188 cm, and weights from 52 to 80 kg. Studies of the myoelectric activity were performed on groups of either 10 or 15 subjects. Simultaneous measurements on the myoelectric back muscle activity, the intradiscal pressure, and the intra-abdominal pressure were performed on four subjects. This arrangement was chosen because of the comparatively large interindividual variation in myoelectric activity and the comparatively small variations between individuals in intradiscal pressure. The number of individuals on which disc pressure measurements were performed was purposely small.

METHODS

Equipment

The equipment used for recording the myoelectric signals, the disc pressure, and the intra-abdominal pressure has been previously described (Andersson et al., 1976b). It included a signal connection and monitoring unit and a 14-channel FM tape recorder. The monitoring unit made it possible to check the signal quality on any two channels simultaneously on an oscilloscope screen. All channels were checked consecutively before and during each recording period. The signals were recorded on magnetic tape for subsequent analysis.

The myoelectric signals were picked up by means of bipolar, recessed surface electrodes (interelectrode distance 20 mm), which were glued to the skin using an alpha-cyanoacrylate adhesive, Cyanolit®. The gap under the electrodes was filled with electrode jelly injected through a hole in the electrode disc. The electrode signals were fed to preamplifiers built into a small box that was strapped to the subject's chest. The signals were further amplified in main amplifiers and fed to the monitoring unit.

The intradiscal pressure was measured by means of a subminiature pressure transducer built into the tip of a needle as previously described by Nachemson and Elfström (1970). The transducer signal was processed in a bridge amplifier and connected to the tape signal monitor and to a two-channel ink recorder.

The equipment for measuring the intra-abdominal (intragastric) pressure consisted of a pressure sensitive radio transducer and a receiver. The radio transducer was incapsulated in a polycarbonate cylinder, 25 mm × 9 mm, that had a metal diaphragm that responded to changes in pressure between the environment and the air contained in the pill. The transducer was swallowed, and the transducer signal was picked up by means of a ferrite antenna and an FM demodulator. The demodulated signal was connected to the tape signal monitor and to the ink recorder.

Prior to recording, the output signals of the pressure measurement equipment were calibrated, as was the ink recorder. During calibration the radio pill was kept at a constant temperature of 37°C.

Evaluation Procedure

Pressure data were evaluated from the calibrated two-channel ink recordings. For the dynamic experiments, characteristic pressures, such as maxima, minima, and base pressures, were read at representative points. For the static recordings, average values during the recording period were estimated. For evaluation of the myoelectric signals, the magnetic tape was played back and the signals were fed into full-wave rectifiers and low-pass filters and further to the galvanometers of a 12-channel ink recorder. The galvanometers responded to the full-wave-rectified and averaged values (FRA values) of the myoelectric signals and were calibrated in microvolt per centimeter so that the signal amplitudes could be read directly from the recording paper. To the paper were added the two pressure data channels. By having all recorded signals on one paper, investigation of the traces for simultaneous events was simplified. All data were treated statistically. Mean values, standard deviations of the means, and 95% confidence intervals were calculated. When statistical hypotheses were tested, the nonparametric Mann-Whitney U-test was adopted and the tests were performed on the 5% level of significance.

Recording Procedure

The guiding needle of the disc pressure transducer was inserted via a lateral approach into the center of the third lumbar disc, the course being followed by TV fluoroscopy. When the tip of the needle had penetrated the annulus fibrosus, the mandrin of the guiding needle was withdrawn and the transducer needle inserted. Zero balancing of the transducer was performed after a few minutes when temperature equilibrium was reached.

The sites for the electrodes were first ink marked. The back was then cleaned with an alcohol-ether solution (4:1), and the electrodes were glued to the skin. Twelve (in the myoelectric studies) or ten electrodes were placed on each subject (Figure 1). They were located 3 cm lateral to the midline on both or one side of the trunk at the levels of T4 and T8, L1, L3 and L5. At the level of L3, a second electrode pair (or electrode) was placed 6 cm lateral to the midline. In some studies, additional electrodes were placed over the transverse part of both trapezius muscles, just above the superior angle of the scapula.

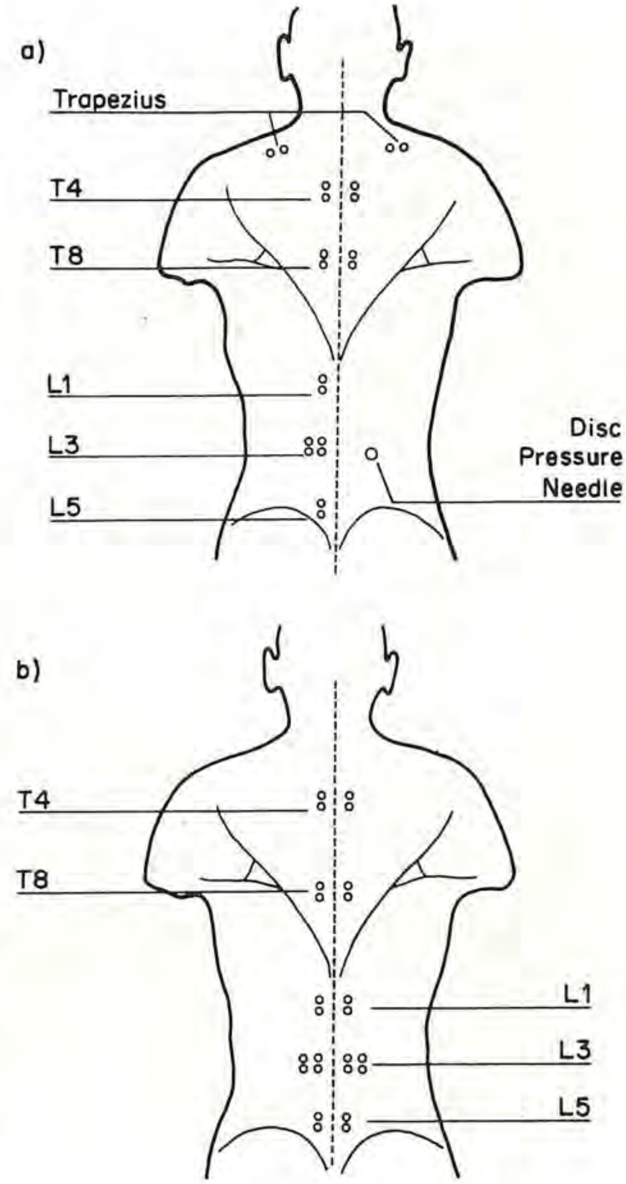


Figure 1. Location of the electrodes and the disc pressure needle in a) the combined studies and b) the myoelectric studies.

The calibrated radio transducer for the intra-abdominal pressure was swallowed. With the ferrite antenna, the subject's abdomen was scanned for locations of highest strength of the radio signal. The antenna was then taped to the skin where it could be conveniently worn during the experiments.

Two series of experiments were performed. In the first, studies were made when the spine was loaded in fixed spinal postures. In the second, lifting was investigated both in static loading experiments (pulling) and in dynamic loading experiments.

In the first experimental series, the subjects were placed in a reference frame in which the position of the feet, legs, pelvis, and spine could all be controlled (Figure 2). They were asked to stand at ease at the center of the vertical support of the frame with the feet parallel and the legs straight. The pelvis was "locked" with a transverse bar and wooden blocks—placed at the anterior superior iliac spines—to prevent lateral movement as well as rotation. The investigations were carried out in four sequences. In the first, the subjects carried a load of 100 N (10.2 kg; 1N = 1/9.8 kg) in each hand. The angle of flexion of the spine was increased from 10 to 50 degrees in increments of 10 degrees as measured with a hydrogoniometer placed over T10.

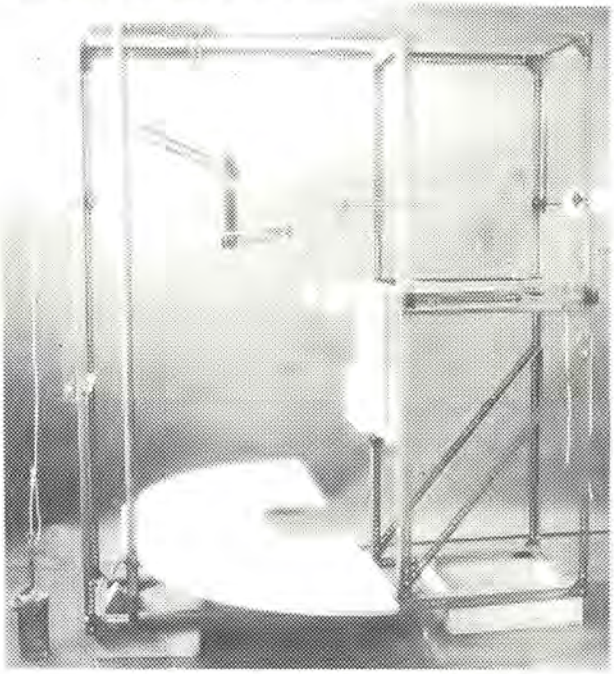


Figure 2. The reference frame.

In the second sequence, the angle of flexion was maintained at 30 degrees while the load in each hand was increased from 0 to 150 N (15.3 kg) in increments of 50 N (5.1 kg). Asymmetric loading of the trunk was then studied with 100 N in the left as well as the right hand while the spine was kept straight in 20 degrees of lateral flexion. Finally, a combination of rotation and lateral flexion was studied. To that purpose, a load of 100 N was placed on a 30-cm-high table, 40 and 50 cm from the subject, and at an angle of 45 degrees from the midline. Rotating the trunk first to 45 degrees, the subject then flexed the back and lifted and held the weight 1 cm above the table. Altogether, 18 different positions were studied in the frame, including upright unloaded standing. Each position was maintained for 30 sec (in the myoelectric experiments) or 12 sec, and after each experiment, a minimum of 1 min was allowed for resting. Recordings at 10 degrees of flexion with a load of 200 N (20.4 kg) were repeated five times during the investigation of each subject.

The second experimental series (lifting) fell into a static and a dynamic part. Static loading was accomplished by asking the subjects to pull on a handle with a force of 400 N (40.8 kg) using both hands symmetrically. The pulling force was indicated on a galvanometer. The distance between the handle and the foot support was 20, 40, and 60 cm in the myoelectric experiments, and 40, 50, and 60 cm in the experiments where the disc pressure and intra-abdominal pressure measurements were also included. At each height, one pull was performed with the back straight and the knees flexed (leg lifting) and one pull with the back flexed and the knee straight (back lifting). Thus, six static experiments were performed, each lasting 30 sec (in the myoelectric experiments) or 12 sec. After each experiment, a minimum of 1 min was allowed for relaxation.

The dynamic loading experiments were of several different types. With the subject standing, 100 N was lifted from 45 cm above the floor to the height of the freely hanging hands. Both hands were used symmetrically, and two methods of lifting were studied—back lifting and leg lifting. One of the subjects repeated the lift while performing the Valsalva maneuver. In another experiment, a weight of 50 N was lifted from a table; both arms were held straight and horizontal and moved in close to the chest and out again. The 50-N weight was then lifted from a 65-cm-high table at different paces. Using both hands, the lift was first performed in less than 1 sec, then in about 5 sec. Finally, both arms were loaded by 100 N and the trunk flexed until a hydrogoniometer (at T10) measured 45 degrees of forward flexion, when the trunk was again extended to the upright position.

RESULTS

Loading in Fixed Spinal Postures

In upright relaxed standing without load, the mean value (standard error of the mean) of the disc pressure was 0.331 MPa* (0.034 MPa) and the corresponding values of the intra-abdominal pressure, 0.20 kPa (0.20 kPa). The mean values of the myoelectric signal amplitudes recorded from the paraspinal muscles in that position were generally low, about 10 μV. The activity picked up from the trapezius muscles was considerably higher, about 50 μV.

*1 Pascal (Pa) = 1 N/m^2 = .102 kg/m^2.

All the measured variables responded systematically to changes in posture and load. When the subjects were loaded with 100 N in each hand and the angle of forward flexion was increased, there was an increase in intradiscal pressure and in intra-abdominal pressure (Figure 3). At the same time, the FRA-values of the paraspinal muscles increased at all levels of the back (Figure 4). The increase in the myoelectric activity was comparatively larger in the thoracic than in the lumbar region. Statistical analysis showed a significant linear relationship between the myoelectric and pressure values and the sine of the angle of flexion.

The intradiscal pressure and the intra-abdominal pressure both increased when the externally applied load was increased at a 30 degree angle of flexion. The relationships between pressures and load were statistically significantly linear (Figure 5). The FRA values increased also at all electrode locations (Figure 6). The increase in myoelectric activity was greater at higher levels of the back and highest for the trapezius muscles.

The disc pressure and the intra-abdominal pressure both increased when the trunk was loaded in lateral flexion as well as in rotation. In these experiments, consistent differences were found in the levels of myoelectric activity recorded on the left and the right side of the back (Figure 7). In the lumbar region, higher FRA values were found on the side contralateral to the load; in the thoracic region, the values were higher on the ipsilateral side. Both trapezius muscles had high levels of

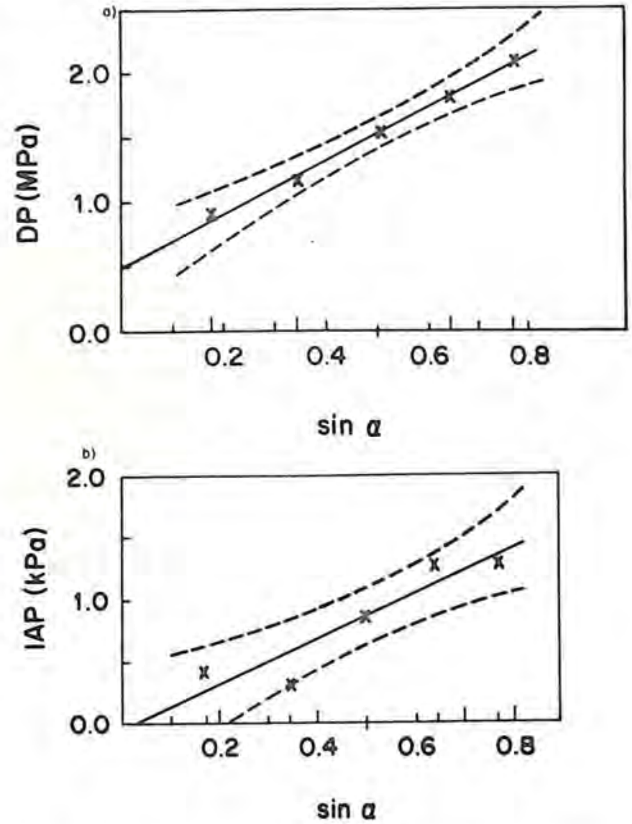


Figure 3. Regression analysis of relation between a) disc pressure and the sine of the angle flexion, and b) intra-abdominal pressure and the sine of the angle of flexion. The mean values are denoted with x. The dashed lines indicate 95% confidence limits for the mean values.

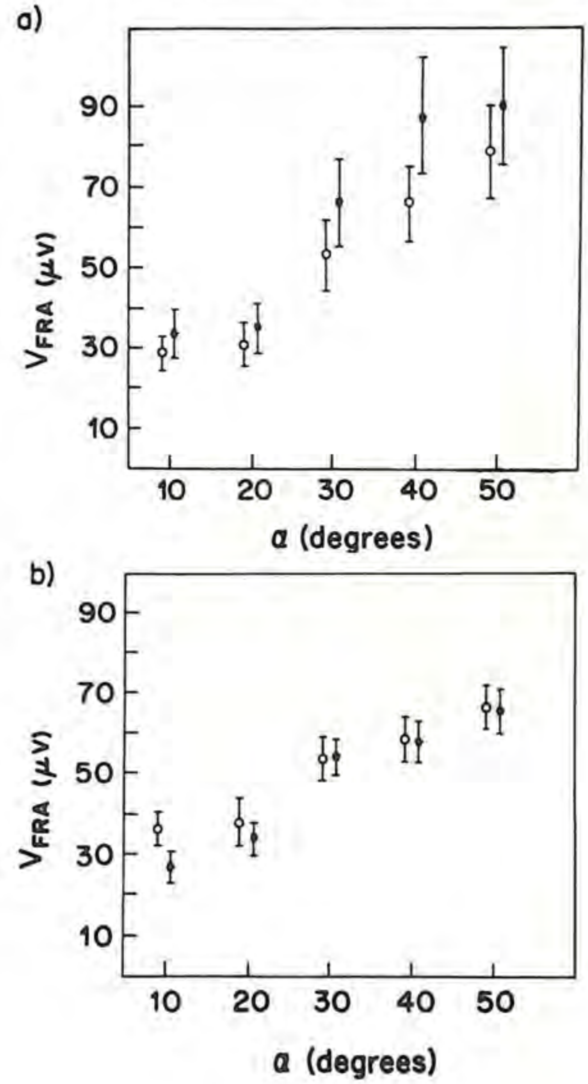
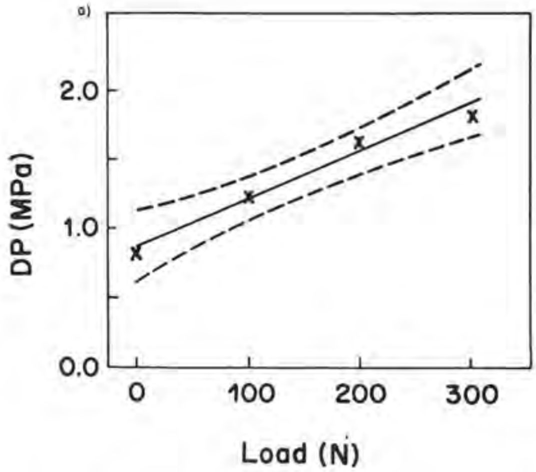


Figure 4. Mean FRA values at a) T8 level, and at b) L3 (3-cm) level, plus and minus one standard error of the mean, related to the angle of flexion. The left side activity is denoted with 0 and the right side activity, with *



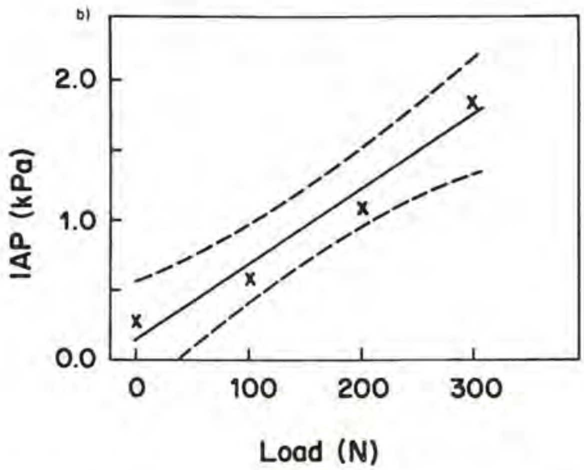


Figure 5. Regression analysis of relation between a) disc pressure and load at 30 degrees of flexion, and b) intre-abdominal pressure and load at 30 degrees of flexion. The mean values are denoted with x. The dashed lines indicate 95% confidence limits for the mean values.

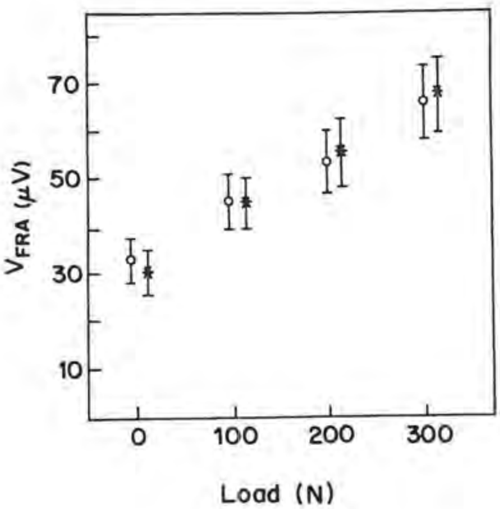


Figure 6. Mean FRA values at L3 (cm) level plus and minus one standard error of the mean, related to the load at 30 degrees of flexion. 0 refers to the right side of the back, * to the left side.

myoelectric activity, but the higher values were always recorded on the ipsilateral side. The disc pressure, the intradiscal pressure, and the FRA values were higher throughout when the trunk was loaded in rotation rather than in lateral flexion.

Lifting (Static Loading)

The FRA values of the myoelectric signals recorded when pulling with the back straight differed considerably from those found when pulling with the back flexed. When the handle was placed 20 or 40 cm above the floor, higher levels of activity were always found when the back was straight. The differences were statistically significant at L1 and L3 levels. When the handle was at 60 cm, higher values were usually found when pulling with the back flexed but the differences were not statistically significant. Figure 8 shows the FRA values recorded at L3 level. There were only slight differences in the activity patterns obtained at the three lumbar levels. The FRA values recorded at thoracic levels were significantly higher than those recorded at lumbar levels when the handle was placed 20 or 40 cm above the floor. With the handle at 60 cm, the activity was often higher in the lumbar region.

The trapezius activities were of the same magnitude and varied in the same way as did the T4 level activities.

The disc pressure values were about the same when pulling was performed with the back flexed as with the back straight; the mean values were slightly higher when the distance between the handle and the floor was shorter. The intra-abdominal pressure differed significantly when pulling at 40 cm; the values were higher with the leg lifting method. At 50 and 60 cm, similar pressure values were obtained.

Dynamic Loading

During lifting of the 100 N weight from 45 cm above the floor to an upright position, the FRA values at all levels of the back and the disc pressure

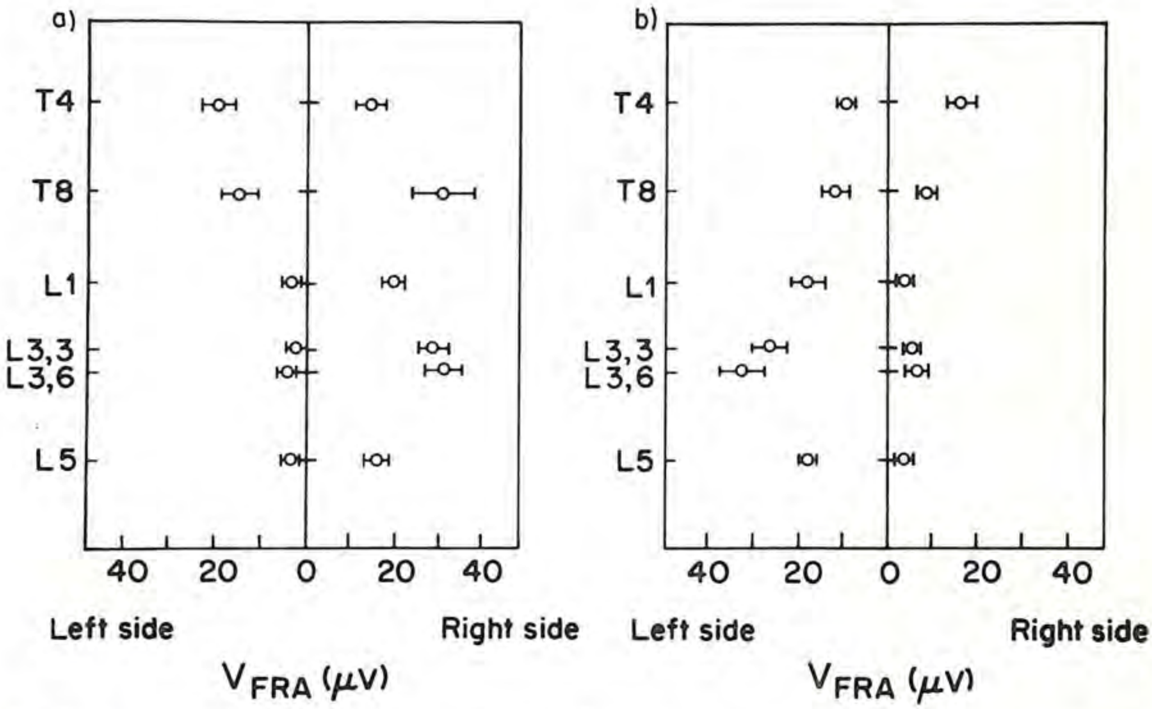


Figure 7. Myoelectric signal amplitudes recorded in 20 degrees of lateral flexion. The weight was held by a) the left arm, and b) the right arm.

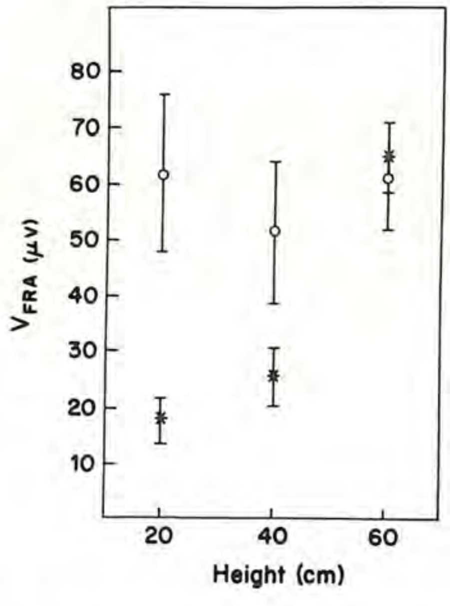


Figure 8. Myoelectric signal amplitudes in different postures recorded at L3 level on the right side. * denotes back-lifting, and 0 denotes leg-lifting.

increased considerably, whereas the intra-abdominal pressure increased only slightly. Usually, peak values in myoelectric activity and disc pressure were reached slightly before the subject had reached the upright position. When the weights were put down again, peak values were reached slightly after the movement was initiated and then decreased gradually. Examples of temporal variations during lifting are shown in Figure 9. When leg lifting was compared with back lifting, no statistically significant differences were observed, although, all means of peak values were higher in back lifting.

When the 50 N weight was lifted with both arms straight and horizontal, high levels of myoelectric activity were recorded and the intra-abdominal pressure and the disc pressure was increased considerably (Figure 10). As the weight was moved in close to the chest, all parameter values decreased and increased again when the weight was moved away from the body. Both the intra-abdominal pressure values and the myoelectric activity values were higher in the extended position than when lifting was performed. Similar values were obtained when the experiments were repeated in a sitting position.

When the weight of 50 N was lifted from a 65-cm-high table using both hands, a change in the pace of the lift did not significantly influence the parameter values recorded.

When slow flexion of the trunk was performed to 45 degrees, there was a gradual increase in the myoelectric activity at all levels of the back, in intra-abdominal pressure, and in disc pressure. The values decreased when the back was extended to

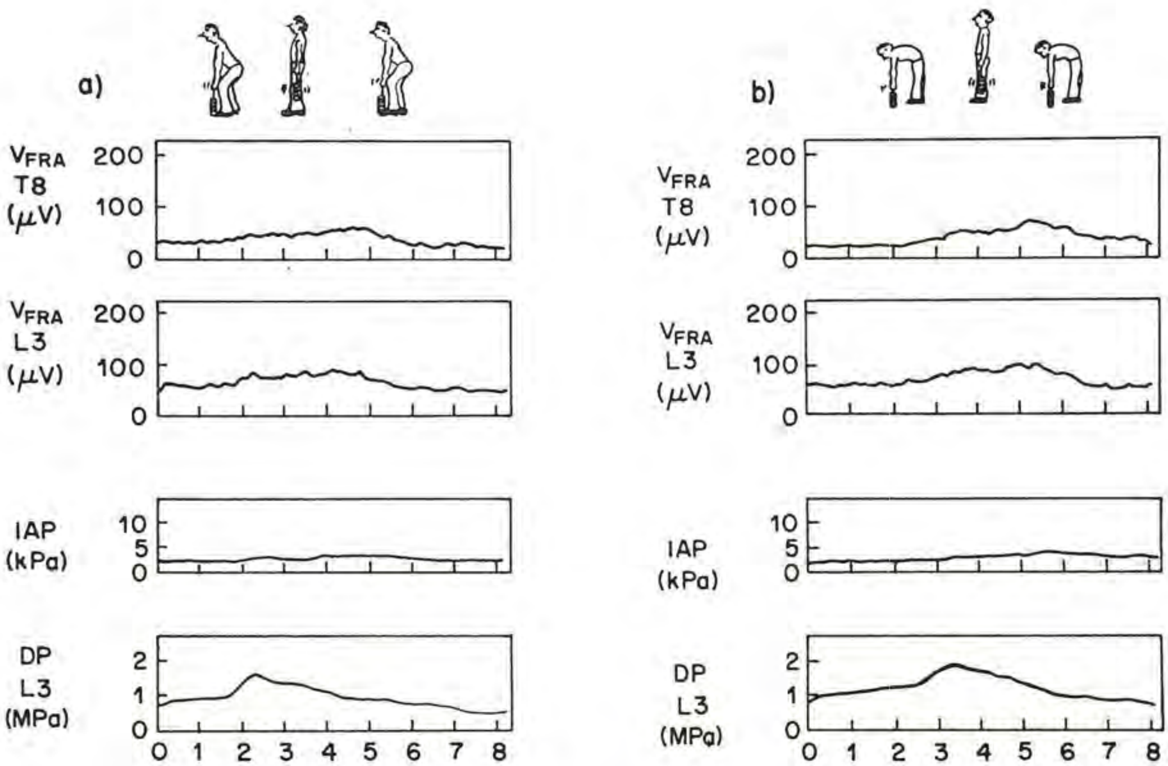


Figure 9. Lifting of 100 N using a) the leg-lifting method and b) the leg-lifting method while performing the Valsalva maneuver. IAP denotes intra-abdominal pressure; DP disc pressure. V_{FRA} denotes myoelectric signal amplitude.

the upright position. The myoelectric activity recorded from the trapezius muscles showed a different activity pattern; the activity decreased in flexion and increased when the trunk was again extended.

DISCUSSION

Methodological aspects have been discussed in the previous papers (Andersson et al., 1976a, 1976b, 1977a, 1977b). Here we will discuss mainly the results and their possible application to manual materials handling. It is important, however, to remember that the studies were either static or dynamic with slow acceleration and velocity.

Acceleration forces may influence all measurement variables. Particularly for the intra-abdominal pressure, initial high peak pressures have been recorded, corresponding to the peak acceleration of a load (Davis and Troup, 1964).

The myoelectric back muscle activities, intra-abdominal pressure, and disc pressure all appear to relate to the moments acting on the spine; the measurement values increase when the trunk moment increases. In the static studies reported here, linear relationships were obtained between each of the parameters and the moment acting on the spine.

Based on the results of previous studies, it must be anticipated that in flexion the linear relationship between the angle of flexion and the myoelectric back muscle activity does not exist when flexion is increased beyond the limits of the present experiment (50 degrees); activity levels would probably decrease (Floyd and Silver, 1955; Morris, Benner, and Lucas, 1962; Okada, 1970; Andersson, Herberts, and Örtengren, 1976a; Andersson, Örtengren and Herberts, 1977a). Indeed, in a few subjects in the present experiments, an amplitude maximum was obtained at 40 degrees of flexion for all spinal levels, except L5.

For the disc pressure and the intra-abdominal pressure, data are insufficient to make inferences from the relationship beyond the range of flexion moment studied. The situation is different from that of the myoelectric activity, however. Although the contribution to the pressures from the muscle activity probably decreases at large angles of flexion, the increasing trunk moments in these positions must still be resisted for equilibrium. Therefore, pressure values would increase in parallel with the increases in moment.

Studies of the different lifting methods favor the leg lifting method. It is important to recognize, however, that the differences were small both in the

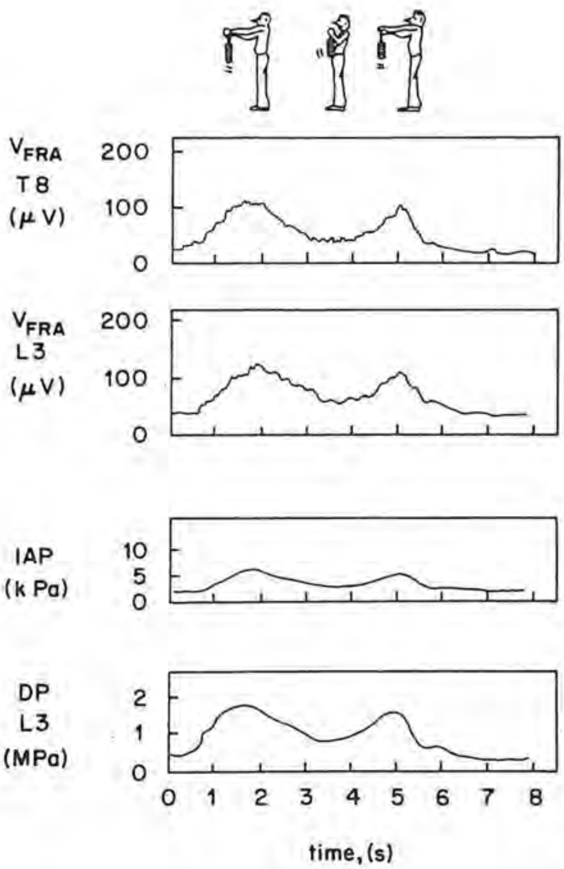


Figure 10. Lifting of 50 N with both arms stretched and horizontal, pulling the weight in close to the body. Standing posture. V_{FRA} denotes myoelectric signal amplitude; IAP, intra-abdominal pressure; and DP, disc pressure.

static and dynamic experiments. The posture of the legs and the spine are probably of secondary importance. In our view, the main advantage of the leg lifting method is that it is possible to bring the object closer to the body. A reduction in the lever arm influenced the measurement parameters much more than the back posture during the lift. Thus, more emphasis should be placed on that aspect in the teaching of "correct" lifting techniques, and efforts should be made to design the workspace and work methods accordingly. This requires also reductions in object sizes and attention to the distribution of load.

Regarding the use of the different methods of field studies, electromyographic and intra-abdominal pressure measurements are the only possibilities; disc pressure measurements must be carried out in laboratory settings. Studies performed at the Volvo assembly line using electromyography are encouraging (Örtengren et al., 1974, 1975). Good, artifact-free signals can be obtained during unrestricted manual work, and the results can then be interpreted together with data on load and posture. The technical difficulties involved and the laborious data analysis preclude general use of this method at present; further development is needed.

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A METHOD OF ESTABLISHING SAFE HANDLING FORCES IN WORKING SITUATIONS

P. R. Davis and D. A. Stubbs

One of the problems arising from considerations of safety during manual handling has been the definition of safe maximum loads. Biomechanical considerations of manual activity demonstrate that, although a load may be lifted or placed with minimal stress by one lifting method, adoption of an alternative technique may impose excessive stress on the body with consequential danger (Davis, 1959; Davis and Troup, 1964; Davis, Troup, and Burnard, 1965; Nachemson and Elfström, 1970; Stubbs, 1975). For this reason many organizations across the world have advocated training in safe manual handling techniques.

Unfortunately, although it is easy to apply an advocated handling method in free space, there are a large number of circumstances in which space limitations necessitate the use of suboptimal body positions. Equally, there remain a large number of lifting tasks in which the load exceeds the advocated safe limits, and yet no satisfactory mechanical handling devices are or can be made available.

To be able to evaluate the safety of all existing manual tasks objectively and to allow safety in future designs of working environments, more rigorous series of criteria are required. These should not only give safe limits for lifting, but also give safe limits for the application of force externally in any direction, with either one or two hands.

We at the University of Surrey have been working towards the goal of defining safe standards for the past 4 years and have now developed a method that appears to allow us to establish limits of safety for any force that can be applied by the hands within the human reach envelope.

METHODOLOGY

Observations by Davis (1959); Morris, Lucas, and Bresler (1961); and many others have shown that during lifting and other manual tasks there is a close correlation between the magnitude of stress on the trunk and the magnitude of intra-abdominal pressure in male subjects. The use of the radio-pill measurement technique has permitted abdominal pressure measurement in field situations, and the pressure/trunk stress correlation is good enough to allow the use of this abdominal pressure measurement as an indirect measure of vertebral stress.

In a detailed study of manual handling hazards in the British construction industry, Stubbs (1973) measured the magnitudes of loads handled and the frequency of operations and observed the postures used in a number of occupations in the industry. In the laboratory, he simulated a number of these tasks and measured their effects on intra-abdominal pressure. He found that the work of carpenters, joiners, plasterers, painters, drivers and crane operators, gangers, and other similar occupations rarely involve the handling of heavy loads (most loads weighing less than 15 kg) and that, in general, the postures used for load handling did not involve stooping. Laboratory observations showed that the handling of such loads in this manner rarely induced peak intra-abdominal pressures in excess of 60 mm Hg.

The work of brick/blocklayers and laborers required 1,000 or more lifts per day of loads up to 70 kg, often in a stooping posture, and laboratory studies showed that a high proportion of these lifts in the observed postures induced peak intra-abdominal pressures in excess of 100 mm Hg. Steel erectors and scaffolders both worked for long periods in stooping positions, but in general the loads lifted were of the order of 33 kg and the frequency of handling was of the order of 300 to 400 lifts per day. Laboratory studies showed that lifts of this magnitude, when stooping, induced peak intra-abdominal pressures of 100 mm Hg or more.

Thus, one can classify the manual loads of these different trades into a light, infrequent handling group, an intermediate group, and a heavy and frequent group. The classification is set out below, together with the number of reported back injuries attributed to manual handling.

Handling group	*Sample size*	*No. of handling back injuries*	*Frequency, No./1000 at risk*
Light	12,542	49	3.91
Intermediate	596	5	8.39
Heavy	10,567	80	7.57

There is a significant difference in back injury rates between the light and heavy group, $\chi^2 = 13.71$ $p < 0.0005$, but the intermediate group is too small for the observed differences to be significant.

There appears to be an increased liability to back injury in those workers in the construction industry sustaining repeated, frequent high-trunk stresses inducing peak intra-abdominal pressures above 100 mm Hg. It, thus, seemed worthwhile to see what magnitudes of loads in different relationships with the trunk would be expected to give pressures of this order during handling tasks.

SUBJECTS

The subjects were healthy males between 17 and 37 years of age, with no history of skeletal disorders; all but 5 were soldiers in service. A series of anthropometric values was determined for each, and these are summarized in Table 1.

Table 1. Anthropometric data obtained from the experimental subjects (N = 120).

*Measurement**	*Mean*	*S.D.*
Age	22.41	4.68
Weight	72.00	10.70
Stature	175.51	6.28
Acromial height	141.58	5.59
Biacromial breadth	41.59	2.28
Acromial grip length	65.60	3.32
Grip span	159.21	7.71
Sitting height	133.76	5.14
Stool height	42.44	2.33

*Age is in years, weight in kilograms; all other values are in centimeters.

The 120 subjects participated in 154 studies: 6 were used in pilot studies, 14 for standing lifts, 14 for sitting lifts, 10 for kneeling trials, 6 for repeated lifting trials, 25 for bimanual pushing/pulling, 6 for standing unimanual lifts, 5 for sitting unimanual lifts, 7 for horizontal forces and unimanual pushing and pulling, and 33 for the validation series.

EXPERIMENTAL DETAILS

Calibrated radio pills (Rigel, model 7040) were swallowed by the subject, and the signals were detected by a model 7020 Rigel receiver. The output was recorded on a Smith's portable Servoscribe recorder (M, type RE501.20).

During the lifts and other activities, trunk posture was recorded photographically with a 35 mm Robot camera positioned laterally to the subject; each frame included a calibrated vertical rod suitably adjusted to allow direct measurement from photographs (Figure 1). Spinal posture was recorded by using spinal markers consisting of rods projecting from flat base plates adhered to the skin over T1, T12, and S1 (Flint, 1963; Davis, Troup, and Burnard, 1965; Kumar, 1971, 1974).

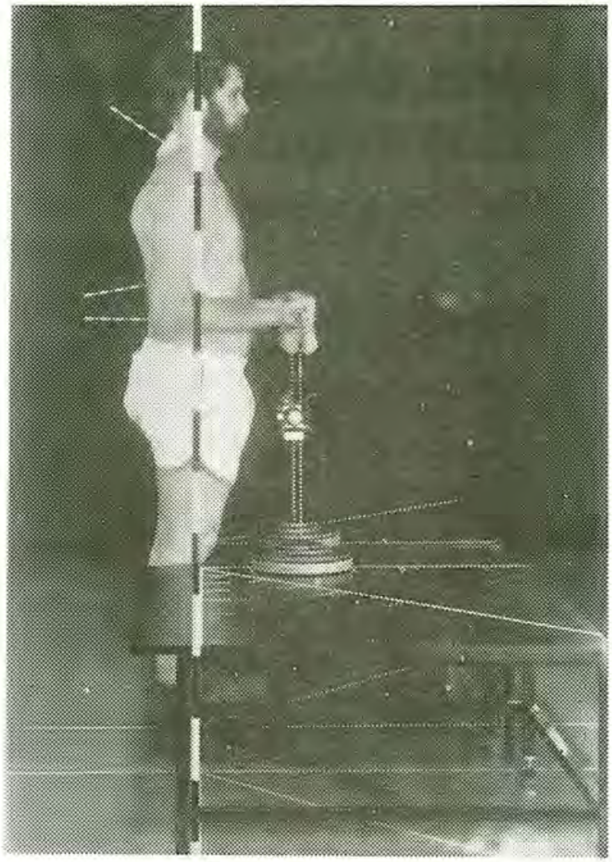

Figure 1. View of the lifting apparatus with the subject waiting to perform a bimanual symmetrical lift with the arms in front of the trunk. Also shown are the spinal markers, calibrated vertical rod weight carriers, and the individual's anthropometric dimensions marked on the tables.

Skin markers were placed over the tips of the acromion processes; these were used as reference points for the arm positions. In all observations except bimanual pushing and pulling, 36 positions were adopted. These comprised lifts, pushes, pulls, or thrusts with the arms in three planes (horizontal (o); inclined 45° upwards (+); and inclined 45° downwards (–)) in front of the trunk. In each of these planes, activities were carried out with the arms in front of the trunk (A position), abducted to 45° (B position), and abducted to 90° (C position). In each combination of inclination and abduction, activities were performed with the grip at 100%, 75%, 50%, and 25% of full arm reach as measured from the acromial markers to the grip at full arm stretch.

Observations were made on subjects when standing, when sitting, and when kneeling. Different series of subjects were asked to handle a series of weights:

- Lifting vertically with two hands (standing, sitting, and kneeling).
- Lifting vertically with the preferred hand (standing, sitting, and kneeling).
- Pushing forward or pulling backward against known forces with two hands (standing and kneeling).
- Pushing forward horizontally against known forces with the preferred hand (standing).
- Applying horizontal palmar thrusts at right angles to the preferred hand (standing).
- Pushing away from the shoulder against known forces with the preferred hand (standing).
- Pulling towards the shoulder against known forces with the preferred hand (standing).

Five different weights were handled in each of the 36 postures for each of these actions. Their magnitudes, determined during pilot studies, ranged from 30% to 90% of mean maximum weight lifted by six subjects in the pilot experiment.

For the seated experiments, an adjustable stool was used. The sitting surface was flat (35-cm deep) and consisted of hardwood covered with 2.5 cm of foam rubber. For each subject, the height was adjusted until the thighs were horizontal. No back rest was used.

For lifting, the two weight carriers were identical. Each consisted of a circular pallet, from the center of which a wire passed to a handle attached to a spool. By winding the wire on to or off the spool, the length of the wire could be altered for any given height of lift.

Before a subject undertook an activity, he was placed in position and his foot (and if sitting, stool) positions were marked. His arm reach was determined, and with his arms fully extended in the A position and horizontal (A,O), the position vertically below his grip was marked on a weight support table. The points directly below his acromial markers were also marked. The 75%, 50%, and 25% arm reach positions were then marked on the table. This procedure was repeated for the 45° inclination positions and for the two abduction positions.

By placing the subject's arms in the required positions, the length of wire needed for the subject was then determined for each. Thus, by placing the pallet on the marked position and unspooling the correct length of wire, the subjects hands were necessarily in the required position, provided the wire was vertical. For each lift, verticality of the wire was checked by two experimenters observing at right angles to each other. For each subject, the order of lifts was randomized, as were the lifting procedures for the different subjects.

For the pushing, pulling, and horizontal force series, weights were placed on a pallet from which two wires ascended to run over pulleys attached to vertical bars. The heights of the pulleys were adjustable. From the pulleys, the wires ran forward to a bar handle. For each operation, the height of the pulleys was adjusted so that the handle was at the correct height for the operation in question, and the platform was marked in a manner similar to that used for the vertical lift experiments.

Groups of subjects then undertook the various operations, and their postures were checked from the photographs. In all activities observed, there was an initial peak of intra-abdominal pressure at the moment that the load began to move; the magnitude of this peak was measured and used for later analysis.

RESULTS

The mean and standard errors of peak pressures for all subjects for each separate operation were determined, and the computer was then used to obtain contours of equal trunk stress as determined from the intra-abdominal pressures. Since, in those postures, the stress observed varied linearly with the weight lifted or force applied, as observed previously by others (Davis, 1959; Morris, Lucas and Bresler, 1961; Davis and Troup, 1965; and Kumar, 1971), these contours indicated positions of equal stress regardless of the magnitude of the weight. In other words, a weight of a given magnitude will impose the same stress on the trunk if held anywhere on a given contour, the distance from the trunk being a percentage of the acromial-grip length of the individual concerned. Certain gaps appeared in a few of the contours because, in particular positions, trunk stresses were small but arm strength was inadequate.

To give "safe" values to the contours, we have inserted those loads that result in a maximum intratruncal pressure of 90 mm Hg in 90% of the population investigated, as this is 10% below the limit value of 100 mm Hg established by Stubbs (1973), mentioned previously.

In a few positions, subjects failed to lift or move the heavier weights although trunk pressures remained low. It was believed that in these cases arm strength was insufficient for the task. In these positions, it was possible to calculate the maximum load that could be moved by the arms, and an arbitrary figure of 90% of this value was incorporated. Interestingly, insertion of this value into the pressure contours results in smooth continuity of the curves obtained.

Having obtained the "safe" maximum contour weights, further experiments were carried out to determine their practicability. The 33 subjects used for these validation experiments were asked to carry out the various activities with loads determined from the contours in each of the 36 arm positions for each activity, while peak intra-abdominal pressure measurements were made as before. The pressures obtained fitted the contours well, and they were accordingly adopted for field use.

These validations showed that the contours are generally applicable to male soldiers within the quoted age range, for single lifting or force application tasks.

Following the establishment of single lift/force contours, we then asked a further series of subjects to perform the tasks repeatedly at different rates, while heart rate and other physiological measurements were made. We found from this that repeated activity at 90% "safe" contour levels causes cardiac fatigue, but that repeated performance of tasks at 70% of the "safe" magnitudes at rates of up to six per minute resulted in heart rate plateaus and no physiological fatigue.

Thus, we are confident that the contours so far achieved can be used for healthy adult males under 37 years of age; that for single tasks, the levels given should not result in spinal damage; and that at 70% of the load magnitudes, the tasks can safely be repeated up to six times per minute over quite long periods.

An example of a contour diagram applicable to young adult males is given in Figure 2.

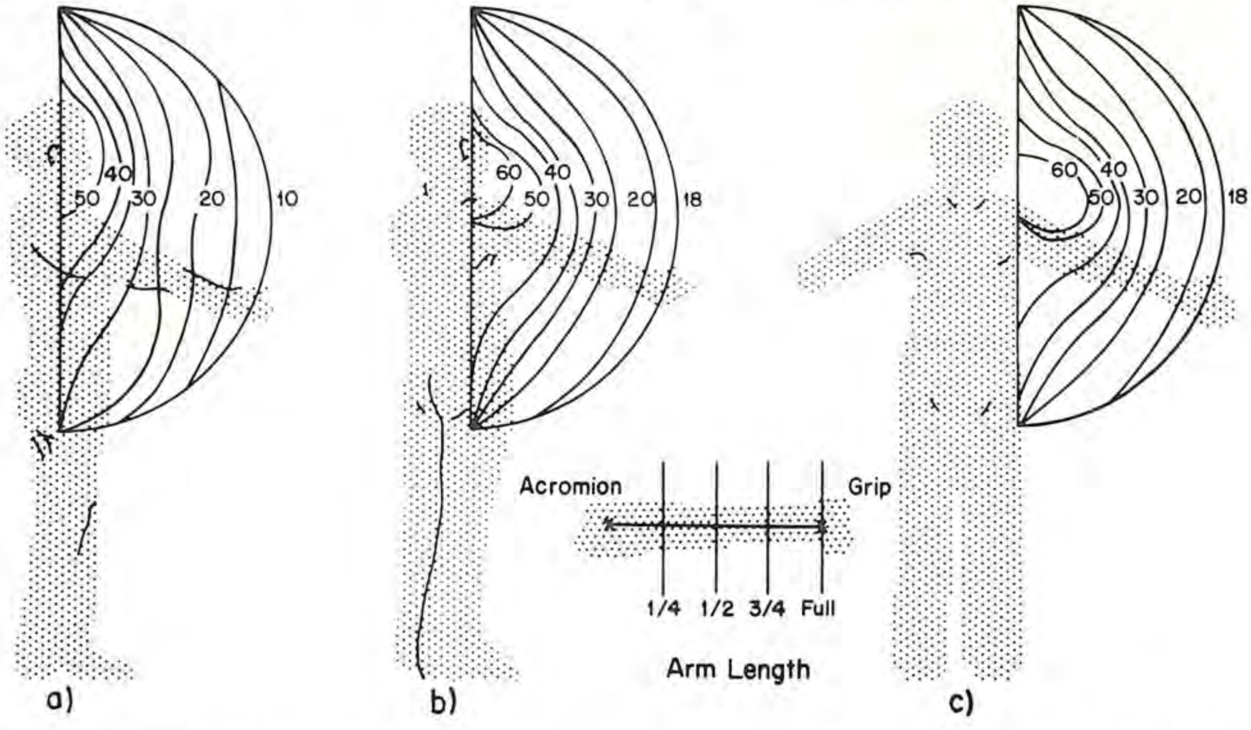

Figure 2. Contours of safe values (kg) for two-handed vertical lifts when standing, or when squatting with the back erect. The weight shown should be divided equally between the two hands. In all cases the two hands should be in similar positions on either side of the body. a) Hands directly in front of the body (sagittal plane); b) Hands in a plane at 45° from the sagittal plane; c) Hands in a plane at 90° from the sagittal plane. The scale indicated in the diagram relates to the distance for the point of the shoulder (acromion) to the knuckles (grip). This shoulder-to-knuckle distance is called the acromial grip length. The 50th percentile acromial grip length is 65.6 cm (5th percentile = 60.1 cm; 95th percentile = 71.1 cm).

DISCUSSION

We believe we are within reach of our objective of having a fully comprehensive guide to task maxima; by establishing contours for other activities and similar contours for different age groups and for females, we hope to establish a fully comprehensive guide to safe lifting levels covering all working situations. The contours could then be used to examine existing situations. Equally, they may also be used in the design of the work places of the future.

ACKNOWLEDGEMENT

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THE ASSESSMENT OF HUMAN STRENGTH

K. H. E. Kroemer

DEFINITION OF STRENGTH

Based on previous considerations (e.g., by Åstrand and Rodahl, 1970; Kroemer, 1967, 1970; Kroemer and Howard, 1970; Caldwell et al., 1974; Herrin et al., 1974), the following definition is proposed:

> "Strength is the capacity to produce torque (force × lever arm) or work by maximal voluntary muscular contractions."

This general description allows defining static and dynamic strength separately:

> "Static strength is the capacity to produce torque (force × lever arm) by an isometric maximal voluntary contraction."

This definition is worded slightly differently, but not changed in contents, from the one by Caldwell et al. (1974) to allow a similar definition for dynamic strength:

> "Dynamic strength is the capacity to produce work by dynamic maximal voluntary contractions."

MEASUREMENT OF STRENGTH

Strength can be assessed either directly at the muscle, or by indirect measures, or at the interface between the human body and the external resistance against which strength is exerted, i.e., at the point of strength application (or transfer).

If the muscular contraction is counteracted by an immovable resistance, the length(s) of the muscle(s) involved remains constant. Such an *isometric* effort can exist only during an equilibrium of forces so that the mass upon which they act remains immobile (static). Hence, the (physical) term static and the (physiological) term isometric are often used interchangeably in strength measurements.

An *isotonic* effort is one of constant muscle tension. Practically, isotonic tension occurs only with an isometric effort of the same muscle. Lifting of weights does not result in isotonic muscle tension (Kroemer, 1970).

If the produced strength is either larger or smaller than the resistance, the length(s) of the contracted muscle(s) changes. In this case, the acting forces are not in equilibrium; the point of force application moves in the direction of the resulting force vector and, hence, the muscles are contracted dynamically. Such a dynamic effort may be single or repeated, one-directional or changing in direction, rhythmic or irregular in sequence, etc. The dynamic work must be described in detail. If the strength is larger than the resistance, the dynamic muscular contraction is called *concentric.* If the muscle is lengthened by an overpowering external energy, the muscular effort is called *eccentric.*

In a static effort, muscle tension is the only variable over time. In static strength testing, muscle tension is usually kept constant over time.

A dynamic effort always involves a time-dependent change in muscle length, as well as a time-dependent change in muscle tension. The variable muscle tension (determining force, or torque) and the variable muscle length (determining displacement) are both functions of exertion time. To assess a dynamic effort, both variables must be measured. (Consider, for example, single "explosive" versus repeated "lifting" efforts.)

For practical reasons, static strength is usually measured at the transfer point, where the human strength is applied to the work tool, equipment, or other resisting structure such as the measuring instrument. This allows the use of inexpensive off-the-shelf transducers and of well established recording and analysis techniques; no physical invasion of the subject's body is necessary. It does not, however, give detailed information about the internal muscular or other physiological events connected with the effort. Hence, numerous methods and techniques have been devised to assess strength directly at the muscle (e.g., EMG) or by indirect measures (e.g., metabolic rates, ratings of perceived exertion).

In the physical sense, strength has vector quality and therefore must be described by both magnitude and direction. For biomechanical reasons, the location of the strength vector must also be described with respect to the nearest (proximal) joint of the human body. This is essential particularly for mathematical models of the biomechanics of the human body because most muscles directly participating in strength production act around a joint producing moments or torques.

A static effort results in torque (force × lever arm) or force (if the lever arm is unknown or not of interest). Measurements in torque units are more meaningful and useful, especially in biomechanics, and should be preferred. No such thing as "static work" exists in physics. There is also no good reason to use this traditional misnomer anymore in physiology; if a static contraction has to be maintained, it can be expressed correctly in the dimensions of torque (or force) and time, and may be called "static effort" or "pulse" (Kroemer, 1970).

A dynamic effort results in work. It may be expressed either in the dimension of force and linear displacement or in the dimension of torque and angular displacement. With our present knowledge about human strength, dynamic capabilities cannot be calculated from known static capabilities (nor vice versa) because different physiological phenomena seem to be the determining factors in either type of effort (Karlsson et al., 1975; Kroemer, 1970; Lind and McNicol, 1976; Petrofsky et al., 1975).

In strength assessment, a continous (analog record of the time history of the test effort is necessary. In static tests, the record must reflect the torque/time history. In dynamic tests, the record must reflect the energy/time history, i.e., the time histories of torque (or force) and of movement (displacement, velocity, acceleration).

Reading only an instantaneous value during the strength test from a display generally can suffice only in pilot tests because in this way too much essential information is lost and errors can be made easily. Furthermore, in most tests the subject is not asked to achieve a single value (such as a peak) but to produce a time integral of the effort (Kroemer, 1970). For example: in static testing, the subject should maintain a maximal strength level for a number of seconds and not try to achieve an instantaneous maximal amplitude; in dynamic tests, the subject should strain to achieve a maximal integral of the torque and displacement curves. Such information requires a continuous record of the test effort.

MAXIMAL VOLUNTARY CONTRACTION (MVC)

All strength measurements require the subject to exert a maximal voluntary contraction (MVC).

Although the intention is clear (i.e., to make the subject volunteer his very best effort in muscle contraction), the question is how to achieve this goal. There is, in fact, close interaction between "maximal" and "voluntary" via the motivation of the subject. It has been shown experimentally that a subject's motivation, and hence the test results, can be greatly affected by the instructions given by the experimenter and by the prevailing experimental conditions (Kroemer and Howard, 1970; Caldwell and Kroemer, 1973). Table 1 lists some of the known or suspected factors affecting motivation (Kroemer, 1974). However, the effects of motivational factors on a subject's performance often cannot be predicted in trend or magnitude. Hence, in the interest of standardization, it presently appears to be best to give factual instructions to the subject and to keep the experimental conditions neutral. (Admittedly, this is not a completely satisfying solution. Perhaps a better one can be found through additional research on motivational techniques and through standardization of an appropriate technique.)

Table 1. Factors affecting motivation.

Motivation factors	*Likely effect*
Feedback of results	+ +
Instructions on how to exert strength	+
Arousal of ego involvement, aspiration	+
Pharmaceutical agents)drugs)	+
Startling noise; subject's outcry	+
Hypnosis	+
Setting of goals, incentives	+ or −
Competition, contest	+ or −
Verbal encouragement	+ or −
Fear of injuries	−
Spectators	?
Deception	?

The terms "maximal" and "voluntary" point to still another aspect. Normally, inhibitions prevent the subject from overexertion and self-inflicted injuries during strength tests. Extreme positive motivation (such as that achieved through hypnosis, keen competition, exhortation, etc.) can override built-in safety mechanisms and may result in damage to muscles, tendons, or other tissue. (This, again, is an argument for keeping the motivational conditions neutral.) In several cases, injuries happened in strength testing when a subject was asked to endure an eccentric effort. Hence, strength tests are recommended only if (a) in static tests, the opposing structure does not move under the subject's effort, and (b) in dynamic tests, the opposing structure moves in the direction of the effort.

A STANDARD PROCEDURE FOR STATIC STRENGTH TESTING

A procedure has been recently standardized for assessing isometric strength (Caldwell et al., 1974). The main body of this procedure is summarized here. Only the definition is changed; it is worded slightly differently from the original to allow the definition of dynamic strength presented above. The meaning, however, is unchanged.

Definition: Static strength is the capacity to produce torque (or force × lever arm) by an isometric maximal voluntary contraction.

"Strength has vector qualities and therefore should be described by magnitude and direction.

"1. Static strength is measured according to the following conditions:
   (a) Static strength is assessed during a steady exertion sustained for four seconds.
   (b) The transient periods of about one second each, before and after the steady exertion, are disregarded.
   (c) The strength datum is the mean score recorded during the first three seconds of the steady exertion.

"2. a) The subject should be informed about the test purpose and procedures.
   (b) Instructions to the subject should be kept factual and not include emotional appeals.
   (c) The subject should be instructed to 'increase to maximum exertion (without jerk) in about one second and maintain this effort during a four second count.'
   (d) Inform the subject during the test session about his general performance in qualitative, non-comparative, positive terms. Do not give instantaneous feedback during the exertion.
   (e) Rewards, goal setting, competition, spectators, fear, noise, etc., can affect the subject's motivation and performance and, therefore, should be avoided.

"3. The minimum rest period between related efforts should be two minutes.

"4. Describe the conditions existing during strength testing:
   (a) Body parts and muscles chiefly used.
   (b) Body position.
   (c) Body support/reaction force available.
   (d) Coupling of the subject to the measuring device (to describe location of the strength vector).
   (e) Strength measuring and recording device.

"5. Subject description:
   (a) Population and sample selection.
   (b) Current health status (medical examination/questionnaire is recommended).
   (c) Sex.
   (d) Age.
   (e) Anthropometry (at least height and weight).
   (f) Training related to the strength testing.

"6. Data reporting:
   (a) Mean (median, mode).
   (b) Standard deviation.
   (c) Skewness.
   (d) Minimum and maximum values.
   (e) Sample size."

CRITICAL REVIEW OF METHODS AND TECHNIQUES

Physical Methods and Techniques

Newton's finding "Force = Mass × Acceleration" (or, "Torque = Moment of Inertia × Angular Acceleration") governs all physical assessments of strength. (Since torque divided by lever arm equals force, the equations for translatory and rotatory movements can be transformed into each other. Hence, in the following text, the term force generally can be substituted by the term torque).

According to Newton, force can be calculated if mass and acceleration are known. This applies either to the case that the acting force produces motion (dynamics) or to the case that all forces acting on the mass are in balance, i.e., the body remains in place (statics). In either case, the active (muscular) force must be counteracted by a reactive force equal in magnitude but opposite in direction so that action = reaction. Quite often, this reaction force is being measured to assess the unknown muscular force. However, measurements of mass or of acceleration (or of its integrals, i.e., velocity and displacement) and/or of time also can be used to assess the acting force.

There are several techniques to provide a compensatory known force to the unknown muscular force. The simplest method is the one used in a balancing scale, i.e., the provision of reaction force via masses acting over a fulcrum. This technique is quite useful if the acting force is maintained over a period of time and can be stepwise counterbalanced by the addition or subtraction of weights. Usually this procedure is limited to static cases of strength exertion.

The most widely used technique to provide a counterbalancing force of known magnitude uses an elastic element that is deformed (usually compressed) by the acting force. If the force/deformation characteristic of this element is calibrated, the acting force can be assessed at each moment from the existing deformation.

In principle, the assessment of the acting force via deforming relies on measuring displacement at the deformed element. This displacement can be measured either directly or can be transformed into another type of signal, for instance into an electrical one. In fact, the transformation of the force input into an analog electric output is by far the most often used technique today. Many commercially available force measuring systems use sensors and transducers of this type. The deformed element is generally of the bent-beam type, often in complex forms such as springs, membranes, etc. The transformation of displacement into the electrical signal is often achieved through strain gages. Industry offers a large selection of strain gages for various purposes. Often strain gages can be attached directly to tools or equipment used at work to indicate the forces and torques applied while working.

The electrical analog output of the force/torque sensor equipped with strain gages facilitates the continuous recording of the results of the muscular efforts, noted earlier as a necessary procedure in strength testing.

Electromyographic Methods

The efferent nerves transmit impulses to the motor endplates in the muscles. These impulses cause the muscle to contract. Frequency and intensity of the impulses determine the amount of force developed and the velocity of the muscle contraction. The amount of force also depends on the number of muscle fibers agitated.

Intensity and frequency of the so-called action potentials associated with the muscle contractions are being measured in microvolts by electromyographic techniques. The electrodes used are either inserted into the muscles (needle electrodes) or are attached to the surface of the skin (surface electrodes) above the muscles.

The frequencies and amplitudes registered in the electromyogram (EMG) indicate the amount of tension, the duration of the contraction, and the degree of fatigue of the muscle in relation to previous or subsequent recordings (Chaffin, 1973; Hopf and Struppler, 1974; Örtengren et al., 1975; Vredenbregt and Rau, 1973). However, difficulties still exist in establishing numerical relationships between EMG and the amount of force exerted, and with respect to the repeatability in intra- and inter-individual measurements. Nevertheless, with future development, EMG techniques should become increasingly useful in assessing the type, duration, and magnitude of muscular strength exertion.

Physiological Methods

A number of physiological tests are being so generally applied that they have, in fact, become standard procedures. They measure energy consumption (O_2 intake, CO_2 output) or cardio-circulatory pheonomena (heart rate, blood pressure), or metabolic byproducts (i.e., lactate), often in combination with each other. (For more information, see, e.g., Åstrand and Rodahl, 1970; Funderburk et al., 1974; Karlsson et al., 1975; Lind and McNicol, 1967; Petrofsky et al., 1975.) However, these methods were not developed to assess "strength" but pulmonary, circulatory, or metabolic characteristics of the whole body. Strength, however, ps generally limited by local (e.g., muscular) capabilities rather than by central functions. Therefore, standard physiological methods are often extremely valuable as procedures accompanying strength tests (Kroemer, 1976; Roebuck et al., 1975) but cannot substitute for such testing.

Psychological (Psychophysical, Psychophysiological) Methods

Instigated particularly by the work in the early 1950's of S. S. Stevens (at Harvard), Ekman (in Stockholm), and their coworkers, researchers have developed procedures that use the subjectively perceived work load as a means to rate the stressor, or stress. In principle, such tests rely on the common experience that the intensity of perception increases with the physical (or physiological) intensity of the load.

In the early 1960's, Borg proposed a model allowing interindividual comparisons and, at the same time, yielding direct intensity levels based on Ratings of Perceived Exertion (RPE). According to Borg and Noble (1974), in the model it is assumed that the subjective range, from the basic perceptional noise level to the maximum intensity level, is approximately the same for each subject. The RPE scale numbers run from 6 (extremely low exertion) to 20 (extremely hard exertion) and are rougly equal to 1/10 of the accompanying heart rates. Although no causal relationship is suggested between RPE and heart rate, correlations between 0.8 and 0.9 have been found in experiments over a wide range of work loads. This seems to indicate that common variables are shared by perceived exertion and the circulatory loading.

With respect to strength exertions, it appears that subjective RPE's are influenced differently according to the type and duration of the effort. If larger muscle groups must work over longer periods of time, pulmonary and circulatory factors seem to contribute predominantly to the RPE values. In short-time work with small muscles, local muscular strain seems to have the highest effects on the RPE ratings.

Snook and his coworkers (1970, 1974) combined subjective ratings with a number of physiological indicators to determine work loads "acceptable" to female and male workers. Their research results indicate that subjective ratings of stressor or stress have a high potential to develop beyond the status of accompanying measures into techniques to assess muscular strength on their own.

Anthropometric and Biomechanical Methods

Hippocrates (about 400 BC) invented a system to classify human body builds. It consists of four somatotypes, supposed to represent the different temperaments found in humans. In this century, Kretschmer introduced his three somatotypes that supposedly represent the main psychological (or psychiatric) characteristics of mankind. He also attributed certain muscular capabilities to these types, e.g., the athletic type is thought to be strong. Both the Hippocrates and the Kretschmer somatotype systems do not rely primarily on physical or physiological criteria and hence do not allow any direct conclusions with regard to the muscular strength. In contrast, Sheldon et al. (1940) used morphological criteria in his somatotyping system which contains three (endomorphic, ectomorphic, and mesomorphic) body builds. Sheldon's system was improved by Heath and Carter (1967) who selected certain anthropometric dimensions to be included in a mathematical model which expressed the body types in numerical terms. In this manner, the subjective classification was converted into a system of analytic description.

Using this most advanced description of body builds, a number of researchers have tried in recent years to find out whether or not physiological characteristics were indeed represented by certain body types. On the basis of a review of the literature and of their own research results, Laubach and McConville (1969) concluded that there are several positive correlations between somatotypes, flexibility, and strength, but that the somatographic classification of the subject does not yield an exact prediction of his muscular strength.

A more direct anthropometric attempt to assess the strength of a subject is to measure the amount of muscle mass (involved in a specific effort) and to establish the biomechanical conditions (such as lever length, pull angle) under which the muscles work. Unfortunately, a number of difficulties have prevented this theoretically promising approach to result in reliable data. This is because, on one hand, lever arms, pull angles, etc., are in many cases not easily measured on a subject. On the other hand, muscle bulk cannot be measured easily either, neither by conventional methods (such as the circumference measures) nor by more advanced techniques (such as radiation). Furthermore, even if the muscle mass were known, one would still have to relate that dimension (expressed, for example, as cross-sectional area) to the contractile capability. A literature search indicates a wide spread of data on contractile force per cross section unit, ranging from 35 N/cm^2 to 180 N/cm^2 (Hettinger, 1972; Roebuck et al., 1975). Finally, it is often difficult to determine which muscles are in fact involved in a strength exertion, and which one of these is the weakest (i.e., limiting) muscle. Under these conditions, assessments of muscle bulk in combination with biomechanical measures cannot, at present, yield exact information on human strength.

In many respects, previously mentioned methods fall, at least partly, into the category of biomechanical measuring methods. The assessment of muscular strength as torques applied around skeletal joints with specific lever arms and pull angles is a biomechanical task. Such information is basic to biomechanical models of the human body pertaining to its geometry, mobility, and strength (Ayoub and Walvekar, 1974; Chaffin, 1969; Chaffin and Park, 1973; Kroemer, 1973; see also the Proceedings of the IEA Congress, 1976). Generally, the assessment of muscular strength transferred to an outside object in form of force, torque, or energy is in many respects a biomechanical problem. Today, in this sense, biomechanics comprise methods and techniques that were traditionally categorized as physiological.

Since the middle 1950's, a number of researchers have found that there is an inverse nonlinear relationship between the proportion of maximal strength that is requested from a subject and the length of time the subject can exert that amount of strength (Monod, 1956; Rohmert, 1960; Molbech, 1963; Caldwell, 1964). Although maximal static strength can be maintained for only a few seconds, exertions of 20% or less of the maximal effort can be maintained for "indefinite" periods. This relationship allows, theoretically, the assessment of the maximal static muscle capability via the time period throughout which a given submaximal force can be maintained. Until recently, most efforts to follow this line of thought experimentally were not successful because large variations occurred in the time measurements. Recently, however, an improved technique was proposed (Laurig et al., 1975) to measure the maximal force capability through the assessment of the endured time. If this method can be validated and applied in the future, it could further facilitate the assessment of static strength.

ERGONOMIC TEST PROCEDURE OF DYNAMIC STRENGTH NEEDED

The foregoing discussion indicates that a number of procedural problems have been solved, although others still remain open. After Caldwell and his coworkers' paper in 1974, the assessment of isometric strength is no longer an open problem; however, for the assessment of dynamic strength, a similar solution is not yet in sight.

The physiological methods currently used in measuring a subject's ability to perform maximal dynamic work cannot satisfy practical requirements to assess his dynamic strength. This dynamic strength is not necessarily limited by pulmonary, circulatory, metabolic, or other such "central" capacities, but rather by the operator's ability (capability and skill) to exert strength with his legs or arms or both, often but not necessarily involving his trunk. Thus, dynamic strength appears to be determined largely by "local" muscular capacities. At present, it seems as if dynamic strength testing might be best defined pragmatically by the type and amount of work that can be performed against an outside testing equipment. Such testing equipment might require from the subject certain torques (constant or variable), or accelerations of masses, in preset cycles or in free squences, in single bouts or in repetitive exertions, around defined body joints or in "free" movements, over preset periods of time, etc. Criteria for the rating of the dynamic test results might be provided by the physically measured output of the test, or by physiological reactions of the body (e.g., reaching of predetermined levels of heart rate), or by subjective rating of the perceived exertion, or by all or a combination of these. Much research needs still to be done to select appropriate methods, procedures, and techniques.

Such selecting of appropriate methods also depends on the required validity (the intended use) of the results. In ergonomics, strength testing cannot be done as a theoretical exercise but must be directed towards the assessment of human capabilities to perform defined work in order to adapt the working conditions accordingly. This requires that the tasks be analyzed for which strength exertion is necessary. No such analysis of the elements of manual materials handling is available today, although it is a typical task in industrial engineering and ergonomics.

Ergonomic tests of dynamic strength must provide information applicable to "the real world." The data must be meaningful with respect to actual tasks such as lifting, lowering, pushing, pulling, and other moving of masses; bending, extending, turning, twisting, and other motions of the body; in various body positions under various environmental conditions; etc. Standardization of test procedures is mandatory, and their results must be useful for setting rules for the safety and health of the operator.

There are still many questions to be solved, such as: How do static test data relate to dynamic data, and vice versa? How do they relate to health problems, such as low back syndrome? How do strength scores, i.e., data indicating "maximal" capacities, relate to ergonomically "optimal" (or: desirable, acceptable, reasonable, permissable, tolerable . . .) conditions? Are different psychophysical continua involved?

Ergonomics adapts the technical environment, especially at work, to man. Ergonomics comprises sciences of man, of work, of engineering, and of their interactions. Ergonomics is man-centered, trans-disciplinary, and application-oriented. Assessing human strength is a typical ergonomic task.

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STRENGTH, DURATION, AND RECOVERY MECHANISMS

C. G. Drury and G. Spitz

THE STRENGTH/DURATION RELATIONSHIP

Since the early 1960's researchers have been quantifying the obvious fact that in static contraction the higher the force required, the shorter the time for which it can be maintained. The classic studies by Rohmert (1960) and Caldwell (1963) have formed the basis for many dozens of research studies which focus more closely on the actual relationship between force and duration, the factors affecting this relationship, and the physiological processes which cause this relationship.

Although this is of obvious theoretical interest, it is pertinent here to state explicitly why it is of interest in a manual materials handling safety context. K. F. Hywel Murrell, one of the originators of ergonomics, used to raise his arm above his head when speaking to industrial engineers and invite them to "rate" him in that task. The point is that static muscular contraction is fatiguing subjectively, it can only be done for a limited duration, and it is not obviously amenable to methods of work measurement or standard setting.

It has been suggested (Drury, 1975) that the problem of designing nondamaging jobs for people involves not exceeding the capabilities of any of a number of potentially limiting subsystems. For manual materials handling these would be:

- nutritional level
- respiratory performance
- cardiovascular performance
- force production of local muscle groups
- failure/strength of the muscular and skeletal systems.

In certain types of tasks this "force production of local muscle groups" can be limiting and thus needs to be quantitatively predictable if safe jobs are to be specified before they are implemented. (Note: this concept of a set of potentially limiting subsystems has been used in a programming model of the lifting task in the interesting formulation of Ayoub and Elshafei (1974) and further refined in the Muth, Ayoub, and Gruver paper in this volume.)

A second reason for reviewing this body of knowledge is its potential contribution to different methods of strength testing. If duration is related to percent of maximum force exertable, then any point on the force/duration curve is a predictor of maximum force exertable, obtained without the use of large forces which could have structural damage potential.

A final reason is that few people are employed just to exert forces: jobs require manual and mental skill as well as muscular work. There is a real possibility that muscular exertion may impair performance on other tasks in the operator's job. Pfitzer, Ellis, and Johnston (1972) showed that exertion of a submaximal force to 40% , 60% , or 80% of the predicted maximum endurance caused a progressive impairment of performance on a measure of manual dexterity. Bloswick and Ellis (1974) extended this to a measure of manual tracking performance and durations from 10% to 90% of predicted maximum endurance. They showed again a progressive impairment of performance and a correspondingly increased recovery interval, ranging up to 30 sec at higher percentages. (See also Davies and Pratt, 1976.)

PHYSIOLOGICAL MECHANISMS DURING STATIC WORK

Because most authors use their results to help elucidate the underlying physiological mechanisms, a fully referenced treatment of physiological mechanisms during static work would be somewhat unwieldy. The following is taken mainly from summaries by Lind and McNicol (1967), Carlson (1969), and Funderburk et al. (1974) for brevity and clarity. When the static contraction is started, two mechanisms come into effect:

1. A tendency for bloodflow in the working muscle to increase by vasodilation, increased blood pressure, and increased cardiac output (caused almost entirely by increases in heart rate).

2. A tendency for the mechanical compression of the muscle fibers to restrict the blood flow to the muscle.

Three levels of effort are of interest:

- 0% to 15% of maximum voluntary contraction (MVC)
- 15% to 70% of MVC
- Over 70% of MVC.

For *any* muscle, no matter what its mass within wide limits, static forces of less than 15% of MVC can be held for very long periods, perhaps hours. In this region, the increasing blood flow is able to compensate entirely for the work output of the muscle and its mechanical compression. All physiological functions rapidly attain equilibrium values proportional to the percent of MVC, and thus, continuous static contraction is possible.

Above 15% MVC, blood flow to the muscle, heart rate, and blood pressure all increase throughout the contraction with blood pressure increasing as a constant function of the *percentage* duration of the contraction. Heart rates can rise by over 30 beats per minute during contractions approaching the limit of endurance. These cardiovascular responses are again largely independent of which muscles are contracting, or even how many muscles are contracting. After the contraction is stopped, blood flow suddenly increases, as would be expected when a mechanical impediment to blood flow is removed. Like other cardiovascular functions, however, it returns rapidly to its resting value with recovery durations beyond 10 min being uncommon. However, full strength may not return to the muscle for considerably longer; a recovery period of over 40 min has been reported (Caldwell, 1970; Lind, 1959; Funderburk et al., 1974).

Above about 70% MVC (the exact percentage is debatable), there appears to be no decrease in performance if the blood supply to the muscle has been prevented by occlusion; this suggests that little or no blood circulation takes place in the muscle beyond this force. This does not mean that the duration is constant for forces beyond 70% MVC; obviously the stores of energy (and storage capacity for waste products) can be used more or less rapidly depending upon the force exerted.

These changes in underlying physiology are mirrored to some extent in the practical effects of various factors on the force/duration curve.

FACTORS AFFECTING THE FORCE/DURATION CURVE

The typical curve relating duration to percent MVC according to Rohmert (1960) can be predicted from:

$$T_{max} = -90 + \frac{126}{P} - \frac{36}{P^2} + \frac{6}{P^3} \qquad (1)$$

(formula as given in Bloswick and Ellis, 1974) where T_{max} is the duration in seconds and P the percent of MVC ($=F/F_{max}$). Alternatively, the equation can be written:

$$(T_{max} + 90)P^3 - 126P^2 + 36P - 6 = 0 \qquad (2)$$

and solved for P given a particular T_{max} value using a standard method for solving a cubic equation. The T_{max}/P relationship is shown in Figure 1 which, according to Rohmert, fits data from a variety of muscles and muscle groups. An alternative formulation from Monod and Scherrer (1965) is:

$$T_{max} = \frac{2.5}{(P - 0.14)^{2.4}} \qquad (3)$$

Although Monod and Scherrer state that their curve and Rohmert's are superimposable, and show a figure to that effect, the two formulas do not agree closely with each other or with their published figures.

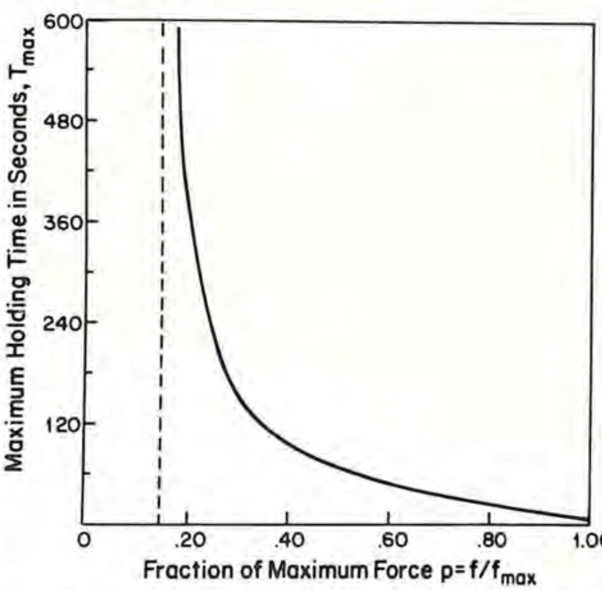

Figure 1. Rohmert's Curve. Maximum holding time for a fraction of maximum force.

Both Rohmert (1973) and Funderburk et al. (1974) indicate that recovery, in terms of percent of MVC that can be reached after contraction, is independent of the particular force/duration used during contraction; it depends only on the state of "fatigue" eventually reached. The time (T_R) needed for full recovery from static work of duration T seconds ($0 \leq T \leq T_{max}$) has been shown by Rohmert to be predictable from:

$$\left(\frac{T_R}{T}\right) = 18\left(\frac{T}{T_{max}}\right)^{1.4} (P - 0.15)^{0.5} \qquad (4)$$

The whole question of intermittent contraction and recovery is dealt with by Monod and Scherrer by dividing the exponent 2.4 in Equation 3 by the proportion of total time for which contractions occur and by changing the 0.14 constant.

The T_{max}/P relationship itself may be independent of the major factors (such as muscle group) used, but it can be affected by a number of factors. Most obvious is the intensity of effort (or level of discomfort or pain) the subject is willing to tolerate. Caldwell and Smith (1966) and Lloyd et al. (1970) and Kirk and Sadoyama (1973) used a scale of pain levels with a fixed number of points and labels varying from "just noticeable" to "intolerable" whereas Janssen and Docter (1973) used a continuous scale of "fatigue" running from 0° to 90° on a moving pointer display. All found a general increase in judged fatigue or pain with duration (T) that generally resulted in a linear relationship. These results suggest that Rohmert's curve may be a limiting case corresponding to "intolerable pain," although care must be exercised in interpreting exact instructions to subjects in different experiments on what is meant by "intolerable."

This can be further elucidated by fitting Equation 1 (or Equation 3) to data available in the literature. Where the actual force exerted is given together with durations then the duration can be used to derive P from Equation 2 and hence, knowing F, to estimate F_{max}. All F_{max} values estimated from the data of an investigator can be averaged to give a mean predicted F_{max} (= $\overline{F_{max}}$). Working backwards from $\overline{F_{max}}$ and F gives P and hence T_{max} from Equation 1; this makes it possible to obtain a predicted and actual T_{max} value for each data point given.

This method has been used to fit Equation 1 to 12 sets of data available in the literature. If the force is given as % MVC, then this is merely substituted in Equation 1 to give a predicted time to compare with the actual time. The results have been split into those five studies based on F and those seven studies based on F/F_{max} (= P) (Table 1). It is obvious that Equation 1 provides a good prediction of mean endurance in most cases.

The Drury (1975) studies are all student or class experiments of manual lifting and include other variables of interest. The first used two different sizes of boxes in a two-handed lift and combined the results using Tichauer's (1971) formula for moments about the lumbar spine. The "static" and "dynamic" results come from a one-handed lifting study of either holding (static) or walking with (dynamic) a compact box. For Table 1, the two lightest weights have been omitted because the absolute magnitude of their times exert a disproportionate influence on the regression equations. The third study combined one- and two-handed lifts into a single equation and, incidentally, confirms in a manual handling context the finding of Lind and McNicol (1967) that physiological changes are independent of the number of muscles contracting. The other studies in Table 1 are either forearm flexion, hand grip, or knee extension studies.

Table 1. Results of regression of measured T_{max} and predicted T_{max} from Equation 1 for 12 studies.

	Study	*Correlation coefficient*	*Slope*	*Intercept*
Calculated from F	Elbel, 1949	.997	1.064	−2.73
	Drury, 1975(a)	.991	1.045	−4.02
	Drury, 1975(b) Static	.990	1.124	−4.91
	(b) Dynamic	.991	0.718	−2.51
	Drury, 1975(c)	.926	1.317	−25.01
Calculated from P	Caldwell, 1963	.999	1.185	−13.87
	Heyward, 1974, day 1	.999	1.318	−0.31
	day 2	.997	1.432	−5.87
	Carlson and McGraw, 1971	.996	2.074	−29.75
	Eason, 1960, original	.999	.508	2.50
	after rest/same hand	.999	.692	−3.95
	after rest/opposite hand	.999	.888	−6.76

Even the anomalies in Table 1 are interesting. For example, the slopes of the lines cluster more closely around 1.0 when the raw F values are used in the calculations than they do when the P values are used, although the variance ratio of 5.888 does not reach significance. This suggests that, where static endurance for holding or carrying is a problem, it may be better to estimate the maximum voluntary contraction (F_{max}) by measuring points on the force/endurance curve than by measuring it directly. Carlson (1969) has shown that there may be different force/duration curves for high-, medium-, and low-strength individuals, again suggesting that F_{max} measured directly may be different from $\overline{F_{max}}$ estimated from the P/T_{max} curve. Heyward (1974), in an extensive review of this part of the literature, found that the correlation between an individual's F_{max} and T_{max} values was not as high as expected.

A final factor shown to have a significant effect on the P/T_{max} curve is muscle temperature. Lind and McNicol (1967) state that at a deep muscle temperature of 27° to 30°C duration is at maximum and that an increase of 10°C can reduce endurance by 60%. Obviously this is an area that needs to be researched more thoroughly to discover the practical effect of environmental and metabolic thermal changes on the P/T_{max} curve in a manual materials handling context.

IMPLICATIONS FOR MANUAL MATERIALS HANDLING

Scheduling of Rest Pauses

Using Rohmert's equations (Equations 1 and 4), work and rest pauses can be scheduled to ensure that neither the static force production mechanism nor its associated recovery mechanism is overtaxed. It is interesting that (looked at in purely mathematical terms) the fraction of time spent in recovery (T_R/T) is minimized when (T/T_{max}) is as small as possible. Obviously many repeated, short duration contractions are less fatiguing than a few long contractions to perform the same total amount of work. This emphasizes again the need for correct workplace design to avoid long duration postural contractions even in work not associated with manual materials handling.

In tasks where a load must be carried over a distance, work/rest scheduling could be accomplished by placing "rest areas" at suitable points along the path.

For any scheduling of work or rest, the required data is F/F_{max} or P. Thus, methods of measurement of these values must be discussed.

Measurement of the P/T_{max} Curve

The need to measure the P/T_{max} curve can, in essence, be reduced to two methods because neither Equation 1 nor Equation 3 contains any free parameters and are completely defined by T_{max}, F, and F_{max}. The methods are:

1. Measure F_{max} by a standard procedure, for example, the methods advocated by Kroemer in the previous paper in this volume. This is theoretically appealing but must be closely controlled for repeatable values and requires equipment to measure time-varying forces accurately or requires a range of weights above and below F_{max} which the subject must attempt to lift.

2. Measure T for some value of F and then predict F_{max} by solving either Equation 1 or Equation 3 for F_{max}. This method is perhaps more realistic as most lifted objects do not change their weight during holding or carrying. It requires only an accurate measurement of a fixed weight and some timing device which can measure times above 6 seconds or so accurately. It has an obvious safety advantage as it can use values of F well below F_{max}, a force potentially damaging to the subject in ways other than over-stressing particular muscle groups. Its obvious disadvantage is the increase in blood pressure associated with sustained static contraction.

This latter method, also proposed by Laurig, Rohmert, and Zipp (1975) and Kroemer (in the previous paper in this volume), deserves careful study.

From a practical viewpoint, it is worth noting that in all studies which quoted a measure of error, the measure of error in T_{max} was proportional to T_{max}. Table 2 shows least squares fit of the equation:

$$\text{standard deviation} = \text{slope} \times \text{mean} + \text{intercept} \quad (5)$$

for all studies quoting standard deviations. It is immediately obvious that the correlations are high and the intercepts are within a few seconds of zero. The slopes are different because "standard deviation" may have come from within-subject variance, between-subject variance, or in a variety of other ways. If we wish to estimate F_{max}, we need to know P as exactly as possible. As the error in T_{max} (= ΔT_{max}) is proportional to T, we have:

$$\Delta T_{max} = kT_{max} \quad (6)$$

Table 2. Relationship between standard deviation and mean endurance.

Study	*Correlation coefficient*	*Slope*	*Intercept*
Elbel, 1949	.998	.558	− 0.80
Drury, 1975(a)	.728	.647	− 2.33
Drury, 1975(b) Static	.981	.393	− 0.43
(b) Dynamic	.982	.266	− 0.37
Drury, 1975(c)	.919	.396	− 3.31
Caldwell, 1963	.999	.352	1.67
Heyward, 1974, day 1	.981	.275	− 2.512
day 2	.986	.315	− 9.354
Carlson and McGraw, 1971	.995	.317	− 6.809

By using simple calculus on Equations 1 and 6, it is possible to estimate the likely error in F_{max}:

$$\Delta F_{max} = \frac{K\,T_{max}\,F_{max}}{(T_{max} + 90)} \quad (7)$$

Thus the relative error in F_{max} is

$$\frac{\Delta F_{max}}{F_{max}} = k\left(\frac{T_{max}}{T_{max} + 90}\right)$$

This is obviously minimized for small T_{max}, that is, for large values of F_{max}. For example, if $k = 0.20$ (a 20% standard deviation in the measured T_{max}), then at MVC where $T_{max} = 6$ sec, the likely error in F_{max} is just over 1%. Where T_{max} is 66 sec (P = 50% MVC), then the likely error in F_{max} is about 8½%.

Thus, to obtain estimates of F_{max} from points on the P/T_{max} curve, we should estimate them as close to MVC as possible. To put this into perspective, for every single reading at $T_{max} = 6$ sec, 46 would be needed at $T_{max} = 66$ sec to achieve the same accuracy.

The difficulties with using points on the P/T_{max} curve to estimate F_{max} rather than a direct measurement are that:

- more measurements are needed,
- the recovery period between measurements is increased, and
- although heart rate changes are not large, blood pressure changes can be large during static contraction.

Against these must be weighted the decreased risk of nonmuscular injury obtainable by asking the subject to use lower forces. There is also the point raised by the data in Table 1 that F_{max} estimated from the P/T_{max} curve may be more consistent with the curve than F_{max} measured directly, possibly because of different emphasis in instructions in the two cases.

What is needed next is a full study combining separate measurements of the F/T_{max} curve and F_{max} to determine the empirical accuracy and hazard of both methods in a controlled setting. An obvious extension of this would be to use the subjective scales of pain during both measurements to determine empirical P/T_{max} curves for various criteria, not just for the physiological maximum of effort.

Other Uses of the P/T_{max} Curve

The consistency of the P/T_{max} curve over different muscle groups suggests its use as a baseline for the measurement of other factors affecting manual materials handling performance and safety.

Obvious extensions would be:

1. A more complete study of the effects of static holding versus dynamic carrying of objects so that different standards could be set (e.g., Drury, 1975).

2. A study of the effects of handles or carrying aids on manual materials handling performance.

3. A study of various specialized loads such as sheet materials, awkwardly shaped objects, etc., to determine the most practical postures for handling such loads.

4. Determination of the effects of environmental and metabolic heat load on static holding performance in realistic situations.

5. Application to nonindustrial situations such as ambulance crews and hospital nurses.

CONCLUSIONS

The consistency of the relationship between proportion of maximum force exerted (P) and endurance time (T_{max}) has been demonstrated in laboratory and practical materials handling situations. Although this has an obvious use in work scheduling and facilities layout, it could also form the basis for alternative measurements of individual performance in manual materials handling tasks which require a load to be held or carried rather than just lifted or lowered.

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METABOLIC INDICES IN MATERIALS HANDLING TASKS

S. H. Rodgers

Measurement of the metabolic requirements of materials handling tasks is of interest for several reasons. First, oxygen utilization is the most direct measure of the job's physical demands. Together with heart rate and blood pressure, it provides the best measure of the effect of the job on the employee's overall physiology. Second, measurement of the oxygen demands of the task can be related to an individual's aerobic capacity in order to determine what percent of capacity it requires. Third, the metabolic demands of manual materials handling tasks affect respiration levels and, thus, influence the acceptable exposure limits to physical and chemical agents in the environment. For instance, the alveolar ventilation level should be taken into account when assessing dust exposures in some bulk handling tasks.

Methods for measuring the metabolic demands of jobs are well documented (Consolazio et al., 1963; Maxfield and Smith, 1967). The amount of oxygen used in a task is the difference between the amount breathed in and the amount breathed out, or

$$\dot{V}_{O_2} = \dot{V}_I \, F_{I_{O_2}} - \dot{V}_E \, F_{E_{O_2}}$$

where

$\dot{V}_{O_2}$ = amount of oxygen consumed in liters/minute, standard temperature and pressure, dry (STPD),

$\dot{V}_I$ = amount of air breathed in in liters/minute (corrected from body temperature and pressure, saturated (BTPS) to STPD),

$\dot{V}_E$ = amount of gas breathed out in same units as $\dot{V}_I$

$F_{I_{O_2}}$ and $F_{E_{O_2}}$ = the fractions of inspired and expired oxygen, respectively, in the air and exhaled gas.

If we assume that the differences between $\dot{V}_I$ and $\dot{V}_E$ are negligible, we can reduce the equation (dropping the minus sign - indicating uptake) to

$$\dot{V}_{O_2} = \dot{V}_E \, (F_{I_{O_2}} - F_{E_{O_2}})$$

$\dot{V}_E$, or minute expired ventilation, can be measured by breathing through a gas flow meter over a discrete time period. $F_{E_{O_2}}$ is measured, using a polarographic method, on a sample of expired air collected during the task; and $F_{I_{O_2}}$ is measured from a sample of room air at the workplace. Because people of different weight will have somewhat different absolute oxygen consumption values for the same task, job $\dot{V}_{O_2}$ demands should be expressed by dividing them by an individual's body weight in kilograms or

$$(\dot{V}_{O_2} \text{ l/min/kg body weight}) \, 1000 = \dot{V}_{O_2} \text{ cc } O_2\text{/min} \cdot \text{kg body weight}$$

For those who prefer to use calories of energy expenditure when talking about metabolic demands of jobs, a factor of 5 times the $\dot{V}_{O_2}$ can be used. Since we assume $\dot{V}_I \simeq \dot{V}_E$ in our estimation of oxygen consumption, the factor of 5 is accurate enough for "ball park" needs.

Oxygen consumption measurements are taken over discrete time periods in most instances, so it becomes important to know what activity is taking place during that time. For each sample period, a detailed analysis should be made of the frequency of handling, weights of objects handled, distances moved (horizontally and vertically), duration of continuous handling, length of rest pauses, and work pace in relation to the expected pace for the job. Information about the environment in which the handling takes place should also be noted, such as levels of chemical or physical agents, shift work schedules, occasional demands (rare product size or seasonal loads), or machine pacing. Oxygen sampling should be done often enough to include representative tasks within the job, as well as to note variations in work load within or across shifts, so that a composite work load can be derived for the shift. At least one resting or light activity sample should be taken to be representative of the rest break metabolic level.

From the above data, one can express the metabolic demands of materials handling tasks in several ways:

1. A weighted working average—not including scheduled work breaks.

2. Total shift working average—including the rest cycles.

3. Peak demands of the job—heaviest loads can be evaluated in relation to their duration and work/rest ratios.

4. Job demands in relation to an individual's aerobic capacity—expressed as percent of capacity required for minutes or hours.

5. Job demands in relation to the aerobic capacities of an industrial population—to assess whether certain job tasks merit redesign.

6. Equivalent whole body demands when mainly arm and shoulder work is involved. Upper body capacity is only 63% to 75% of whole body capacity. So, an oxygen demand of 9 cc/min•kg is equivalent perceptually to a whole body effort level of 13 cc/min•kg body weight. This is useful primarily for evaluating the relative effort levels of a number of tasks using different muscle groups.

Over the past 15 years, Waldo J. Nielsen and other members of the Human Factors Section (of Eastman Kodak Company) have measured several jobs involving manual materials handling tasks. Table 1 illustrates four of these jobs and includes information about their metabolic demands and how they were modified. The first job was partly machine paced, and the total 8-hr work load was great enough to put it beyond the 33% of maximum capacity guideline (Åstrand and Rodahl, 1970) for 70% of the potential work force. Methods and workplace changes brought it within the guideline for most people.

The second job illustrates materials handling tasks where a majority of effort is done by the smaller muscles of the arms and shoulders. Although total work load was not excessive for most people (based on whole body aerobic capacity), local fatigue of the arm and shoulder muscles made it advisable to redesign the workplace to distribute the load more evenly. The third job illustrates a peak load that makes an otherwise suitable job difficult for some people.

Table 1. Metabolic demands of some manual materials handling jobs (average oxygen demands in cc O_2/min/kg body weight).

Job	*No. jobs studied*	*No. people studied*	*Weighted working average*	*8-hour average*	*Peak demands*	*Peak duration, min*	*Correction for upper body work*	*% of Individual's capacity $\bar{x}$ (range)*	*% of Population for whom job was suitable* (range)*	*Comments*
Handler case sealing and palletizing	3	5	14.4	13.6	16.6	30 min	—	22% (15-40)	30%	Machine paced to some extent. Job modified to bring it within the capacities of most people.
Wrapping and packing	9	20	9.3	8.8	12.2	20 min	13.2	24% (10-33)	80% (30% based on arm capacity)	Standing arm work—workplace design changes improved job to reduce stress on arm and shoulder muscles.
Cafeteria attending	2	3	7.9	7.1	12.9	40 min	10.6	20% (15-23)	95% (57% based on arm capacity)	Time pressure stress—dish machine unloading hardest activity. Job redesign reduced effort requirements on dish machine.
Coal car unloading	1	4	24.4	17.1	28.5	30 min	—	30% (25-35)	5%	Studied in winter and summer—peak loads are main difficulty. Modifications in job have reduced some of this stress.

*Assumes an average of 33% of aerobic capacity as upper limit for 8 hours of work.

Redesigning that one aspect of the job by improving environmental factors, reorganizing the work, and providing rest breaks brought it within most people's capacities.

The last job also includes high peak loads, but it is complicated by additional demands for strength and several environmental factors that further increase the physical load. Although some modifications have been made to reduce the physical effort, selection of personnel for this job appears to be more feasible than redesign of the job.

Table 2 illustrates some individual responses to a number of material handling tasks which we were asked to evaluate because there were questions about the work-load suitability. It can be noted that the majority of people studied were working below the 33% of maximum aerobic capacity limit for 8 hr (even when corrected for upper body capacity), but some individuals exceeded the guideline. Where this happened, recommendations to reduce the effort were implemented to accommodate more people. We have observed that most people will select a level of effort that keeps them within the 33% of maximum capacity guideline and will also integrate other factors such as:

- the biomechanical aspects of materials to be handled—grasping characteristics, size, etc.
- environmental characteristics of the workplace—heat, hours of work, chemical agents, pacing, etc.
- the individual's physical fitness level
- the individual's skill level—training and experience on the job
- the individual's activities outside of work—second job, housework, etc.

Table 2. Observed individual work loads on materials handling tasks*

Job	*% Capacity over 8 hr*	*Comments*
Box car loading and unloading	30, 31, 38, 37, 29, 26	Recommended increased rest allowances.
Shipping case handling	28	
Handling packing supplies	43, 32	Redesigned job to reduce effort.
Plastic sheet wrapping and packing	21	
Wrap and pack film and paper products	27, 25, 20; 28, 23, 21; 28 18; 27, 23; 23; 33, 28; 23, 18, 23, 10; 30, 29, 29	Recommended workplace design changes.
Mail delivery	23, 16, 15, 15	
Palletizing and case sealing	40, 19; 16; 19, 15	Redesigned sealing station.
Machine loading—trays or rolls	27, 17; 33, 28	Recommended handling aids.
Unloading coal	35, 32, 30, 25	High peak loads. Recommended increased rest allowance—improved equipment.
Bulk chemical handling	28, 21; 47, 38; 28, 21, 21	Recommended job redesign.
Furnace charging and unloading	56, 34, 31	Redesigned job and workplace.
Scrap handling	25, 24	
Metal working—grinding, fabricating, passivating	25, 32, 23, 25, 30, 19	Increased rest allowance for static effort.
Cafeteria and building cleaning	38, 31; 51, 30, 23, 19	Recommended improved equipment, increased rest allowances.

*Based on heart rate and energy expenditure data. In all examples except a few wrap and pack jobs, effort evaluations were made because of concern about work load suitability.

The metabolic measure of work load in materials handling can help sort out the contribution of some of these other factors to the total stress (measured by heart rate, for instance) of a task.

Because people self-regulate their metabolic load and because the oxygen demands are only part of the stress associated with manual materials handling, it would be difficult to use this measure alone to set safety standards or to give guidelines for personnel selection. The methodology, although not particularly difficult, requires investment in equipment costing up to $5000, making it impractical for many people. Being able to estimate the metabolic demands of jobs based on observation would be useful, though, for evaluating safe work loads and the interaction of effort and environmental factors. Using an effort estimation method developed from some of our own job studies (Rodgers et al., 1976), we can describe manual handling tasks according to their intensity and duration requirements, as shown in Figure 1. The inten-

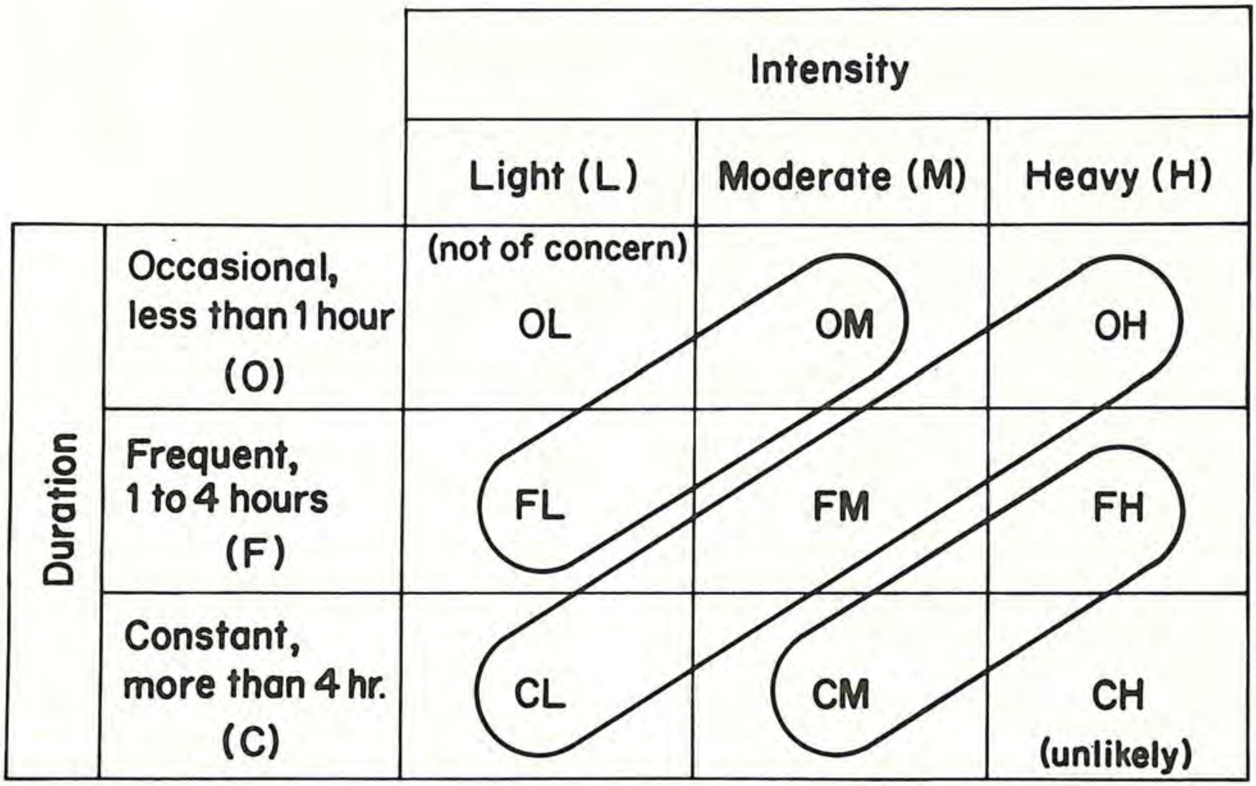
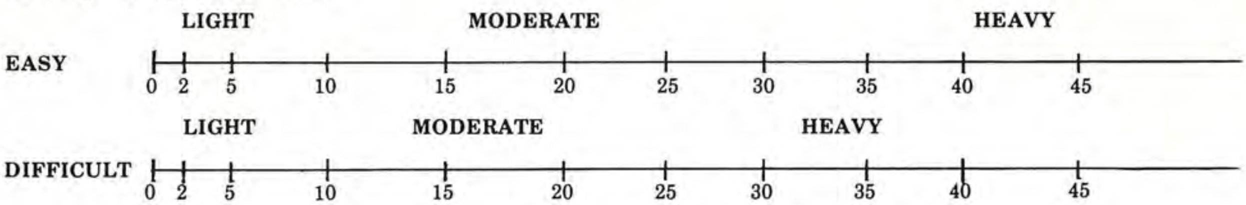


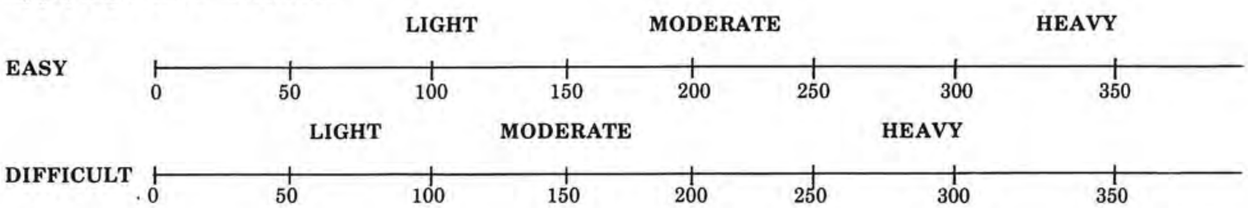
Figure 1. Categories of effort.

sity of the effort is classified as light, moderate, and heavy and can be broken into the following parameters:

Lifting—Kilograms mass



Applying Force—Newtons



Easy handleability = good handholds, comfortable postures, below should height, compact load, stable.

Difficult handleability = poor grasping surface, awkward postures, high lifts, shifting load, large dimensions.

Duration is classified as occasional (less than 1 hr per shift), frequent (1 to 4 hr), and constant (more than 4 hr). In terms of oxygen consumption, the matrix of intensity and duration seen in Figure 1 can be reduced to five equivalent categories, two of which are either unlikely or not of concern. The metabolic demands for the three remaining categories of effort are:

$$FL, OM \simeq 7 \text{ cc } O_2/\text{min} \cdot \text{kg body weight}$$

$$CL, FM, OH \simeq 10 \text{ cc } O_2/\text{min} \cdot \text{kg body weight}$$

$$CM, FH \simeq 12 \text{ cc } O_2/\text{min} \cdot \text{kg body weight}$$

With this rough categorization of effort for manual materials handling tasks, one can get an estimate of the physical effort required for a given job. Because the pattern of handling varies, one must also consider the work/rest patterns, biomechanical aspects of the handling task, and environmental conditions in constructing a safety standard. Personnel selection techniques would have to consider not only work load in relation to aerobic capacity, but also small muscle strength which might be more critical in many tasks than endurance.

In summary, the metabolic demands of manual handling tasks should be among the factors considered when developing a safety standard. Methods of estimating the demands are more practical than are the requirements to measure them. Close attention should be given to the distribution of effort in time, the biomechanical requirements of the tasks, and the interaction of environmental factors when interpreting the metabolic data and determining job suitability.

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CARDIOVASCULAR AND RESPIRATORY LIMITATIONS ON MUSCULAR FATIGUE DURING LIFTING TASKS

A. R. Lind and J. S. Petrofsky

INTRODUCTION

Most industrial work involves a combination of rhythmic and isometric exercise. Studies in the laboratory of either rhythmic exercise (treadmill walking or bicycle ergometry) or isometric exercise (typically, hand-grip dynamometry) show that cardiovascular and respiratory responses to the two types of exercise are quite different. Rhythmic exercise, performed to fatigue, elicits maximal heart rate and little or no increase in mean blood pressure (Åstrand, 1960), and although minute ventilation achieves high levels, there is no hyperventilation until very high levels of work are achieved. During fatiguing static effort, there is a modest increase in heart rate while mean blood pressure increases dramatically to reach very high levels at the point of fatigue (Lind, 1970); in addition, there is a marked hyperventilation, indicating an inefficient pulmonary function (Wiley and Lind, 1975). When static effort is performed concurrently with rhythmic exercise, the responses characteristic of static effort are superimposed on those of the rhythmic exercise (Lind and McNicol, 1967; Wiley and Lind, 1975). This finding is a remarkable one since the muscle mass involved in static, hand-grip contractions is small, whereas that involved in rhythmic exercise, either on a treadmill or a bicycle ergometer, is large.

The bulk of physiological evidence concerning permissible levels of work in industry comes from laboratory studies in which the work performed is highly rhythmic in nature (Åstrand, 1960, 1967). But much of the work in industry involves varying degrees of static component which can affect physiological responses (Atzler et al., 1927; Simonson and Lind, 1971; Petrofsky et al., 1975). There is no information of a systematic nature concerning the physiological responses to lifting; the present study is concerned with that problem.

METHODS

Subjects

Four male medical students volunteered to be subjects in these experiments; their ages, heights, and weights are listed in Table 1. All subjects were informed of all experimental procedures and were medically examined, including an ECG stress test, before being accepted in the study; each signed a statement of informed consent before the investigations began.

Table 1. Heights, weights, and ages of the four male subjects.

Subjects	*Height, cm*	*Weight, kg*	*Age, years*
JR	177.8	79.1	27
SL	190.5	93.2	23
KM	167.6	58.64	23
KK	177.8	74.6	21

Training

All subjects were first trained in lifting and cycling and isometric contractions of the hand grip and back muscles over a 12-week period.

Procedures

There were two main parts of the investigation.

1. First, a series of experiments was intended to compare the oxygen uptake, minute ventilation and heart rate during lifting tasks with those during bicycle ergometry. In both lifting and bicycling, the energy cost of the work ranged from light to maximal. The lifting work consisted of raising a box (30 × 18 × 18 cm) from a height of 6 cm to 60 cm. Although the subjects were told to lift in any way they pleased, all four subjects chose to lift by the bent-back technique. The rates of lifting were set between four lifts per minute and whatever rate

was necessary to establish the maximum working capacity for each individual at each given box weight. The box weights were 6.82, 22.73, and 36.36 kg (15, 50, and 80 lb). Bicycling work was performed on a Monark bicycle ergometer at a speed of 50 rpm with belt tensions varying from 0 to 6 Kp. The duration of the lifting and bicycling in these experiments was 4 min to allow $\dot{V}O_2$ to reach a steady state value.

During both types of work the volume of the expired air was measured during the last half of the second, third, and fourth minutes of work. The subjects breathed through a Collins low-resistance mouthpiece and the gas volumes were measured on a Parkinson-Cowan dry-gas meter. Samples of expired air (200 ml) were collected in glycerine coated syringes connected to a manifold on the exhaust side of the gas meter. The CO_2 in the expired air was measured on a Goddard Capnograph CO_2-analyzer and the O_2 on a Beckman E2 O_2-analyzer. The heart rate was measured over 15-sec intervals from a continuous recording of the ECG.

2. Once the oxygen cost of lifting had been determined, we extended the duration of the lifting bouts to 1 hr to examine the degree of fatigue during such work. Four work loads were chosen for each of the three box weights: 25%, 40%, 55%, and 70% of the $\dot{V}O_2$ max recorded for the separate box weights. During these experiments, we measured the oxygen uptake, the minute ventilation, and the heart rate in the 4th, 29th, and 59th min of work, in the same manner as described above. In addition, the arterial (fingertip) lactate concentration and the isometric endurance for the hand grip and the back muscles were measured.

To assess isometric endurance, the maximum strength (maximum voluntary contraction, MVC) was determined before lifting as the largest of two brief (3 sec) maximal efforts. Thirty seconds after the one-hour lifting bout, a sustained contraction was held to fatigue at 40% MVC. In one series of experiments, isometric strength and endurance were measured for the hand grip, using a portable, strain gage hand-grip dynamometer similar to the one described by Clarke et al. (1958). In the replicate series of experiments, we assessed the isometric endurance of the back and arm muscles. In this case, the subject sat on the floor with his legs straight and his back at an angle of 90° to his legs. The subject then held a pair of wooden handles (separated by the same width and set at the same distance from the soles of his feet as he encountered during the 1-hr vertical lifting tasks) and tried to pull the handles in the same manner as during lifting. Tension was measured as the deformation of a stainless-steel bar connected through a universal joint to the handles.

In addition to the experiments described above, several experiments were performed where the subject attempted to lift for 4 hr; only one weight of box was used, 22.73 kg, (50 lb). The subjects worked at rates which required between 40% and 60% of their maximal oxygen uptake as determined in the first series of experiments. Lifting was maintained continuously for 50 min of each hour. The oxygen uptake, minute ventilation, and heart rates were measured during the 4th and 49th min of each hour; lactates and isometric endurance of the hand grip were measured at the end of the 4th hr of work, as described above.

RESULTS

Oxygen Cost of Lifting

The average oxygen uptake for different work loads while lifting boxes of 6.82, 22.73, and 36.36 kg (15, 50, and 80 lb) at different rates and during bicycle ergometry is shown in Figure 1. Each point in this figure illustrates the mean of two determinations on each of the four subjects; the response of any one individual showed the same pattern as that of the mean. The highest oxygen uptake recorded during bicycling averaged 3.67 ± 0.38 l/min for the

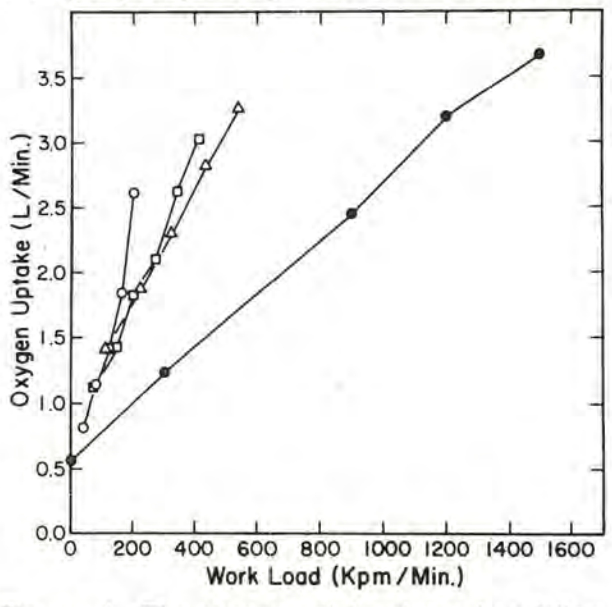

Figure 1. The oxygen uptake shown in relation to the work load for lifting boxes weighing 6.82 (○), 22.73 (□), and 36.36 (△) kg at rates between 4 and 60 lifts per minute. Each point in the figure represents the mean of two experiments on each of the four subjects. For basis of comparison, the results of similar experiments performed on the bicycle ergometer are shown (•).

four subjects. In contrast, the oxygen uptake at the maximum working capacity during lifting was always less than that for cycling for all subjects, with the lowest values being recorded during lifting the lightest boxes. The maximum $\dot{V}O_2$ averaged 2.61 ± 0.52, 3.06 ± 0.35, and 3.17 ± 0.36 l O_2 /min while lifting boxes of 6.82, 22.73, and 36.36 kg (15, 50, and 80 lb). The rates of lifting associated with maximum working capacity were 52-60, 24-30, and 20-24 lifts/min for boxes weighing 6.82, 22.73, and 36.36 kg, respectively. The limitation on working capacity reported by our subjects was their inability to lift at higher rates for the 6.82 kg boxes, whereas fatigue in the arms or hands appeared to be the limiting factor for lifting the heaviest box weight. For any given work load, the oxygen cost of lifting any box weight was much higher than the cost during bicycle ergometry. There was also a significantly higher $\dot{V}O_2$, at any given work load, when the lightest boxes were lifted as compared with that experienced with the other two box weights. This was reflected in the calculated mechanical efficiencies for lifting and bicycling which averaged only 4.95 ± 0.61, 6.57 ± 1.04, and 7.49 ± 1.4% for lifting boxes of increasing weight, whereas it was 19.19 ± 2.65% for cycling.

Ventilation

As with the oxygen consumption, the minute ventilation for all subjects was highest for any given work load when they were lifting the lightest boxes; also the minute ventilation for lifting any given box weight was substantially higher than for bicycling (Figure 2a). However, when the results were expressed in terms of the oxygen uptake, there were only small differences in the minute ventilation between lifting any of the three box weights and the cycling. This is illustrated in Figure 2b, which shows the relationship between the average minute ventilation and the $\dot{V}O_2$ for the four subjects when lifting the boxes weighing 6.82, 22.73, and 36.36 kg as well as during bicycling at 50 rpm at the same work loads described in Figure 2a. For any one individual, or for the group means as shown in this figure, the ventilation was linearly related only to the oxygen consumption and not to the type of work. At the maximum working capacity for lifting tasks, the minute ventilation was substantially less in lifting tasks than it was for bicycling; the lowest ventilation was associated with lifting the lightest boxes.

Heart Rate

The average heart rates for the four subjects during lifting and cycling at the various absolute work loads are shown in Figure 3a. As with the minute ventilation, the heart rates were higher for a given work load when lifting than when cycling. But, as seen in Figure 3b, the heart rates were linearly related to the oxygen cost of the work for both lifting and cycling. However, although the relationship between oxygen cost and heart rate was linear for all tasks examined, the highest heart rates were associated with lifting boxes of 36.36 kg (80 lb) and

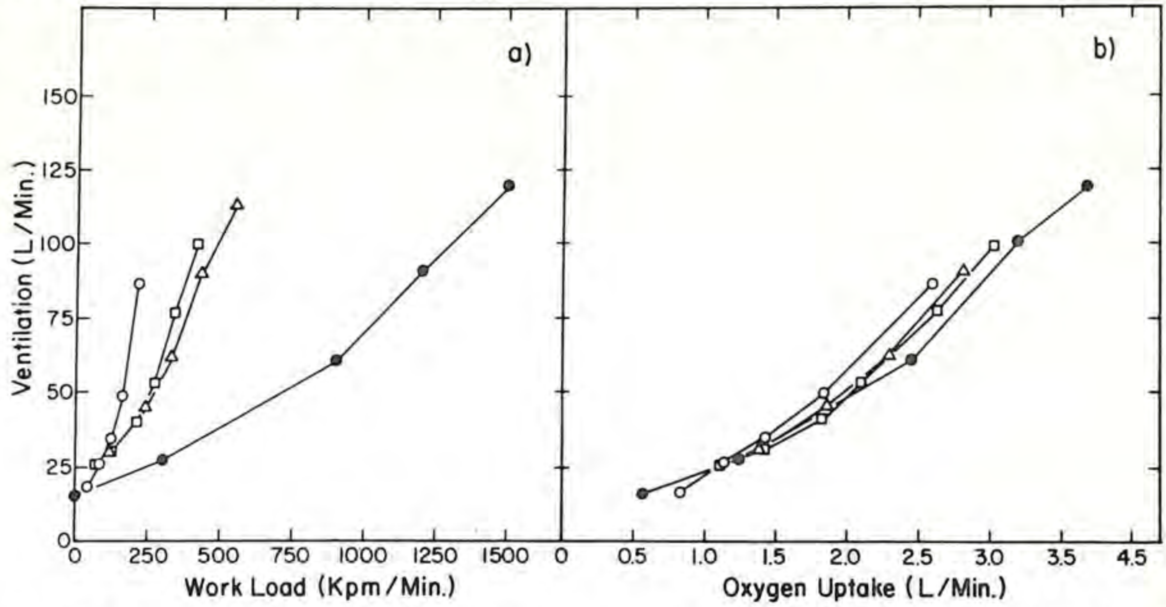

Figure 2. Figure 2a. Minute ventilation recorded at different work loads while lifting 6.82 (○), 22.73 (□), and 36.36 (△) kg boxes and during bicycling (•). Each point in the figure illustrates the mean of two determinations on each of four subjects. Figure 2b. Minute ventilation plotted against $\dot{V}O_2$ of the work loads described in Figure 2a.

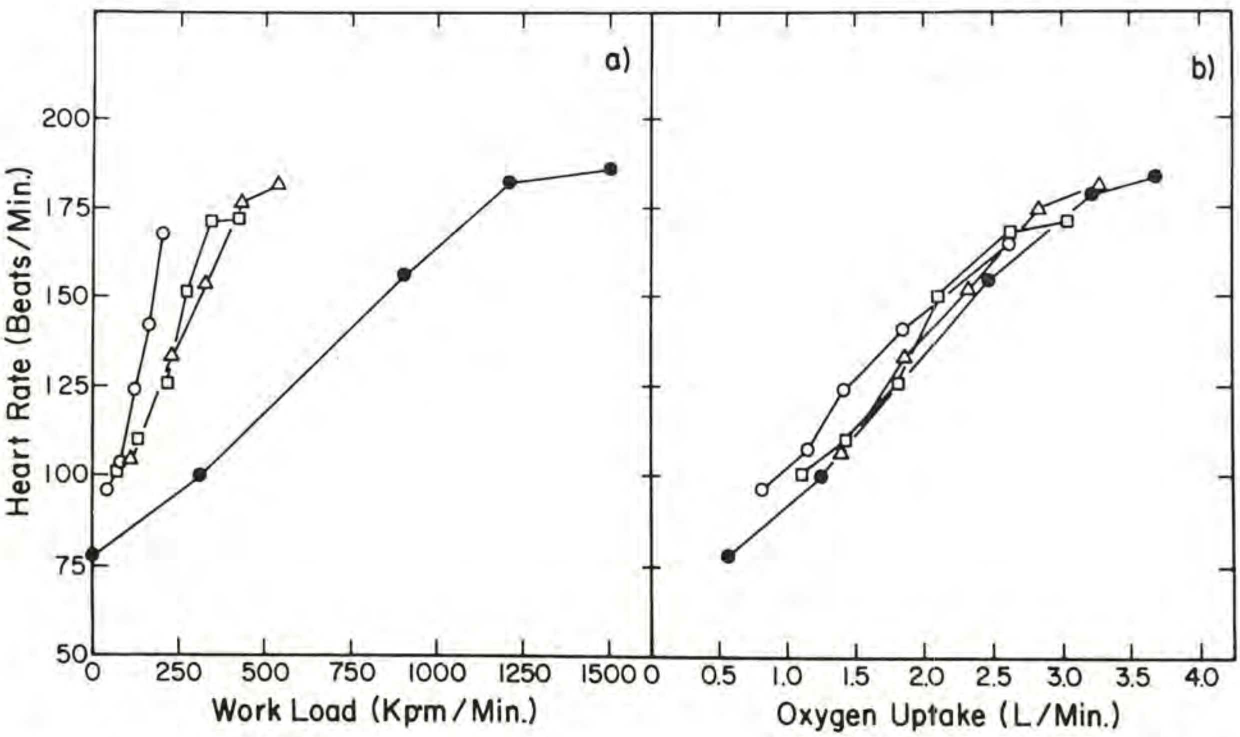

Figure 3. Figure 3a. The heart rate recorded at different work loads while lifting 6.82 (○), 22.73 (□), and 36.36 (△) kg boxes and during work on the bicycle ergometer (•). Each point in this figure illustrates the mean of two determinations on each of four subjects. Figure 3b. The same heart rates plotted against $\dot{V}O_2$.

during bicycling; in these circumstances, the highest heart rates were about 15 beats/min above the values found during lifting boxes weighing 6.82 kg (15 lb).

Fatigue During Lifting

During experiments in which the subjects lifted for 1 hr, the oxygen uptake, ventilation, and heart rates each reached steady state values after about 5 min of lifting and maintained those values throughout the 1-hr period at the two lightest work loads (25% and 40% $\dot{V}O_2$ max). However, with the heavier work loads (55% and 70% $\dot{V}O_2$ max), all three measurements increased steadily during the exercise. For example, when the subjects lifted any of the three box loads at 70% of their respective maximum oxygen uptakes, the oxygen uptake, ventilation, and heart rate each increased by more than 15% in the course of 1 hr. These findings were also reflected in the arterial lactates and the body temperatures.

Figure 4a shows the arterial lactate concentrations after the 1-hr lifting experiments. Where the work load required more than about 1.5 l O_2 /min, lactates were markedly elevated at the end of the hour. The exact work load where this occurred was different for each box weight; the only common denominator was that the work load above which arterial lactates began to rise was about 50% of the $\dot{V}O_2$ max for each given weight of box (Figure 4b).

Figure 5 shows the average isometric hand-grip endurance of the four subjects measured 30 sec after the end of the lifting exercise for each of the box weights and the isometric endurance of the back and arm muscles following lifting the 22.73-kg (50 lb) boxes for an hour. For purposes of comparison, the isometric endurance here has been normalized in terms of the average isometric endurance for two control contractions for each of the four subjects performed on a day when they did no lifting. For all box weights, the isometric endurance in the hand grip and the arm and back muscles decreased inversely with the work load. The reduction in endurance was large (50%) and similar for both types of isometric endurance at work loads of 70% of the $\dot{V}O_2$ max for a given box load. But at all the work loads below 70% $\dot{V}O_2$ max, the endurance for the hand grip always showed a greater reduction in endurance than did the back and arm muscles, implying a greater degree of forearm than back fatigue under these circumstances. The greatest reduction in hand-grip endurance was associated with lifting the 36.36 kg (80 lb) boxes.

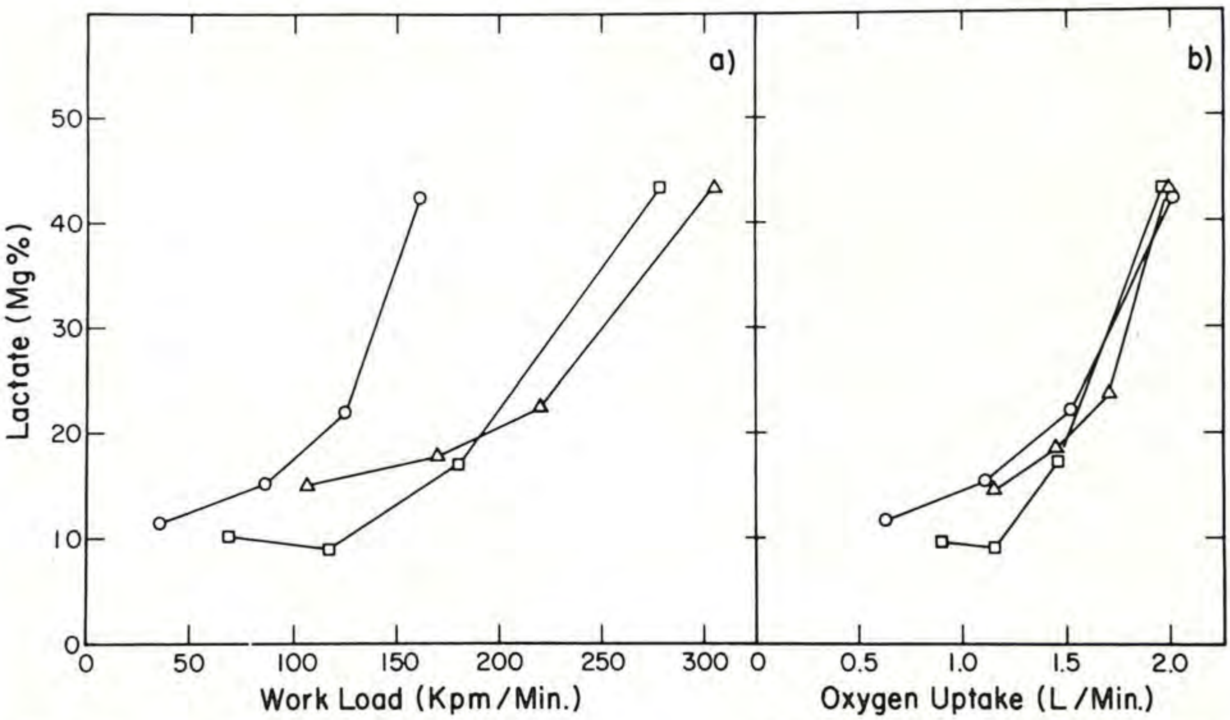

Figure 4. The mean arterial lactate concentrations measured between 15 and 30 seconds after the completion of a 1-hour bout of work lifting the 6.82 (○), 22.73 (□), and 36.36 (△) kg boxes. Figure 4a. Results plotted against the absolute work loads. Figure 4b. The same data plotted against percent $\dot{V}O_2$ maximum.

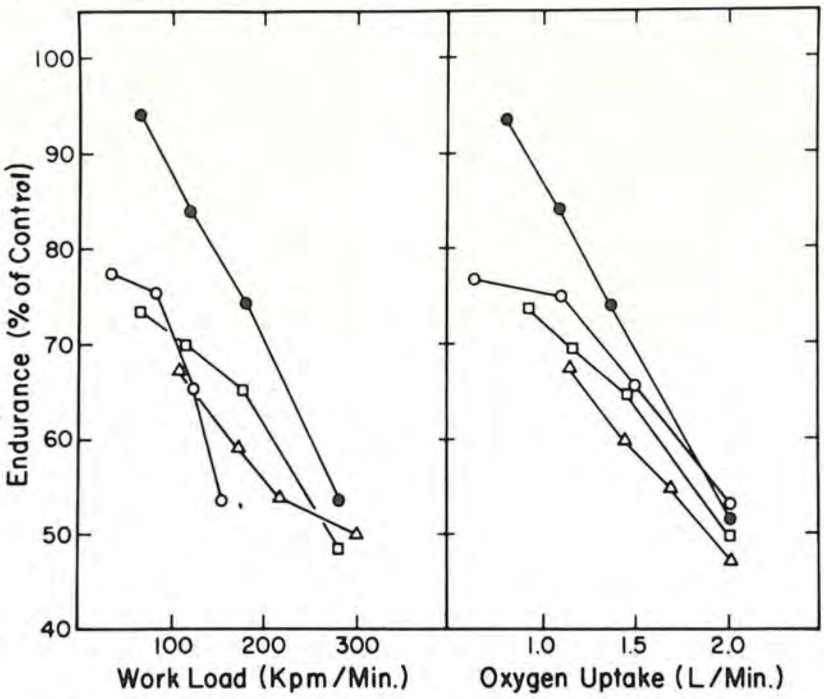

Figure 5. The isometric endurance at a tension of 40% MVC following 1-hour bouts of lifting. Illustrated are the isometric endurances of the handgrip muscles after lifting the 6.82 (○), 22.73 (□), and 36.36 (△) kg boxes as well as the endurance for isometric exercise of the arm and back muscles following 1-hour bouts of lifting the 22.73 kg boxes (•).

In the final series of experiments, the work load was extended to a maximum of 4 hr to find which work load could be tolerated for an extended period of time. Only one weight of box (22.73 kg (50 lb)) was used. The work load was set initially at about 50% of the maximum working capacity for each subject. If that work load was maintained for 4 hr, the experiment was repeated on another day with the work load being increased by some 5% of the aerobic capacity of the subject. This procedure was repeated until the work load could not be maintained for the 4-hr test period. The results of these experiments showed that, as predicted by the 1-hr experiments, no subject could complete the work at loads greater than 60% $\dot{V}O_2$ max and the average tolerable work load was 54 ± 7%. Above these critical work loads, the oxygen uptake, minute ventilation, heart rate, and isometric endurance increased rapidly and the work could not be continued for a period of 2 hr.

DISCUSSION

The data presented here shows 1) that for any given work load, the energy expenditure is much greater for lifting than for bicycling and 2)) that the maximal working capacity and $\dot{V}O_2$ max is lower for lifting than for bicycling. These were predictable findings, but the present study has documented them in a systematic manner. The reduction in efficiency in lifting as compared with that of cycling is, of course, because much of the energy expended is necessary to move portions of the body. In consequence, lifting the lightest box resulted in the lowest work efficiency. The limitation of working capacity was different for each of the box weights. At the lowest box weight, the matter depended simply on the rate at which the body could move, whereas at the highest box weight, the limitation was fatigue in the arms. Another factor which may be responsible for a lower $\dot{V}O_2$ max during lifting is a restriction of respiratory chest movements.

The general principle that some given fraction of the $\dot{V}O_2$ max is important in assessing fatigue has been upheld in these experiments. The data on both respiratory and cardiovascular responses indicate that in men accustomed to lifting the level of work which corresponds with the development of fatigue is some 45% to 55% of the $\dot{V}O_2$ max for lifting boxes at each of the weights examined. These findings agree well with the principle put forward by Åstrand (1960).

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PSYCHOPHYSIOLOGICAL INDICES—WHAT PEOPLE *WILL* DO

S. H. Snook

INTRODUCTION

Three types of measurements have generally been used in studies of manual materials handling: performance measurements (strength and endurance), physiological measurements (heart rate, oxygen consumption, body temperature), and psychophysical measurements (subjective and behavioral responses). Unfortunately, all three types of measurements have their disadvantages, and for this reason, it is good procedure in any experiment to include an example of each type. Many of the physiological measurements, for example, can only be used on repetitive tasks involving large muscle groups. The performance measurements, on the other hand, often require subjects to exert maximum forces which might not be acceptable to or healthy for many workers. The special controls necessary for psychophysical measurements frequently restrict them to laboratory investigations instead of field studies. However, the one big advantage of the psychophysical measurements is their application to all types of industrial tasks without the necessity of maximum exertion.

PSYCHOPHYSICAL METHODOLOGY

Psychophysics is a very old branch of psychology that is concerned with the relationship between sensations and their physical stimuli; very rarely is this a one-to-one relationship. According to modern psychophysical theory (Stevens, 1960), the strength of a sensation (S) is directly related to the intensity of its physical stimulus (I) by means of a power function: $S = kI^n$. The constant (k) is a function of the particular units of measurement that are used. When plotted in log-log coordinates, a power function is represented by a straight line, with the exponent (n) being equal to the slope of the line. Exponents have been experimentally determined for many types of stimuli—for example, 3.5 for electric shock, 1.3 for taste (salt), and 0.6 for loudness (binaural). Of interest here is the perception of muscular effort and force, both of which have been found to obey the power law, and both with an exponent of approximately 1.6 (Borg, 1962; Eisler, 1962). Stevens and Cain (1970) found that the exponent for duration of hand grip is about half the exponent for force of hand grip.

Psychophysics has been applied to practical problems in many areas. For example, the scales of effective temperature, loudness, and brightness were developed with psychophysical methodology (Houghton and Yagloglou, 1923; Chapanis, 1959). Psychophysics has also been used by Borg (1962, 1973) in developing ratings of perceived exertion; by the U.S. Air Force in studies of lifting (Emanuel et al. 1956; Switzer, 1962); by the U.S. Army in studies of treadmill walking (Evans, 1961, 1962); and by Caldwell and his associates in the development of effort scales (Caldwell and Smith, 1967; Caldwell and Grossman, 1973).

The application of psychophysical methodology to manual materials handling tasks in industry has been pioneered by the Liberty Mutual Insurance Company. Of the several different types of psychophysical methods available (Stevens, 1958), the Liberty Mutual studies have utilized a combination of the methods of adjustment and tracking. Essentially, the subject is given control of one of the task variables, usually the weight of the object being handled. All other variables such as frequency, size, height, distance are controlled. The subject then monitors his own feelings of exertion or fatigue and adjusts the weight of the object accordingly. This approach is not unlike that of job enrichment, where one listens to the worker and obtains the feelings of the person who actually performs the task. In many respects, the worker is the expert, because only the worker knows how his or her body is responding to a specific task.

THE PSYCHOPHYSICAL EXPERIMENT

In the psychophysical experiment, it is necessary to simulate the industrial task as realistically as possible. If lifting is being studied, then the task should be a dynamic lift through a given distance, not just an isometric pull. If a repetitive task is being studied, then the task duration should be similar to that found in industry. Subjects will always over-estimate their capabilities during short duration tasks. The danger of a Hawthorne effect (where subjects are overly motivated by the experimental atmosphere) is always present in a psychophysical experiment. The best experiments will have the same subjects returning for several days or weeks in order to overcome the novelty of a laboratory environment. Measurements should never be taken at the beginning of an experiment.

The choice of a dependent variable (which the subject controls) depends upon the purpose of the experiment. Task frequency (pace) is often used in studies of maximum work load (Snook and Irvine, 1968). Task height has been used in studies of pushing (Kroemer and Robinson, 1971). Object weight is commonly used in studies of maximum weight (Snook et al., 1970; Snook and Irvine, 1967; Snook and Ciriello, 1974a; Ayoub et al., 1976). There are several methods for adjusting the weight of the object. During lifting and carrying experiments, the subject is often provided with lead shot (or similar material) which can be put in or taken out of the object being handled. Sometimes the shot is packaged in small bags for easier handling (Emanuel et al., 1956; Switzer, 1962). If the shot is packaged, the weight of the package must be small enough to allow the subject sufficient sensitivity of adjustment, and to reduce undesirable visual cues (such as counting the number of bags in the object). Visual cues can also be reduced by building a false bottom into the object being handled and randomly varying the amount of weight in the false bottom (Snook and Irvine, 1967).

At the beginning of a psychophysical experiment, subjects tend to accept the initial weight (force, frequency, etc.) of the object that is given to them. They should be encouraged to make changes in the object weight by starting them with a very light or a very heavy weight. Tasks under study should be run at least twice; once with a heavy initial weight and once with a light initial weight. The order should be randomized. If the results of the subject's first test are within 15% of the second test, the average of the two results is recorded. Otherwise, the results should be discarded and the test re-run at another time. The heavy initial weights and the light initial weights should both be randomized.

The type of subject used in the psychophysical experiment is very important. If the experiment is studying industrial tasks, then industrial workers should be used as subjects. Students and military personnel have different perceptions of industrial work. A medical examination should ensure that subjects do not have back or cardiopulmonary disorders. Instructions to the subjects must be very specific and carefully worded to ensure complete understanding. Generally, they are instructed to work as hard as they can without straining themselves, or without becoming unusually tired, weakened, overheated, or out of breath. Several days of training should be provided so that subjects can gain experience at monitoring their own feelings and adjusting the object weight accordingly. During the training period, subjects should begin with short duration and/or low frequency tasks and gradually build up to the required tasks. As in industry, new subjects should not be required to maintain a full workload during the first few days. Otherwise, sore muscles may contaminate the experimental results.

PSYCHOPHYSICAL RESULTS

Psychophysical data have been collected from several different types of manual materials handling tasks (viz., lifting, lowering, pushing, pulling, carrying, and walking) (Snook et al., 1970; Snook and Ciriello, 1974a). Data from the lower lifting task (from floor level to knuckle height) have been selected for summary in this paper because of the close association between lower back pain and lower lifting.

Table 1 shows the results from several different psychophysical experiments conducted at Liberty Mutual. These experiments were similar in that (a) they all used object weight as the dependent variable, (b) they all used the same compact object (a 34.3- × 48.3- × 14.0-cm tote box complete with

Table 1. Psychophysical results from low lifting tasks performed at Liberty Mutual.

Sex	*Task frequency*	*Mean weight (kg)*	*SD*	*Source*
M	14 sec	20.4	5.7	Snook, Irvine, and Bass, 1970
M	16 sec	21.1	5.4	Snook, Irvine, and Bass, 1970
M	60 sec	24.4	5.9	Snook, Irvine, and Bass, 1970
M	15 min	29.9	5.0	Snook and Irvine, 1967
M	8 hr	39.2	10.7	Snook, Ciriello, and Fulco, 1976
F	14 sec	15.3	3.1	Snook and Ciriello, 1974a
F	16 sec	15.4	2.6	Snook and Ciriello, 1974a
F	60 sec	16.9	3.1	Snook and Ciriello, 1974a
F	8 hr	20.7	9.6	Snook, Ciriello, and Fulco, 1976

two 17.8- × 4.1-cm handles and a false bottom), and (c) they all used the experimental guidelines described in the previous section. When the results in Table 1 are plotted on a logarithmic time scale (see Figure 1), a linear relationship is revealed. Notice that the slope for the female data is considerably less than the slope for the male data. Mean heart rate during the fast task frequencies was 112 beats/min for males and 117 beats/min for females. Energy expenditure was 300 Kcal/hr for males and 240 Kcal/hr for females. These values are consistent with physiological fatigue criteria (Snook and Irvine, 1969).

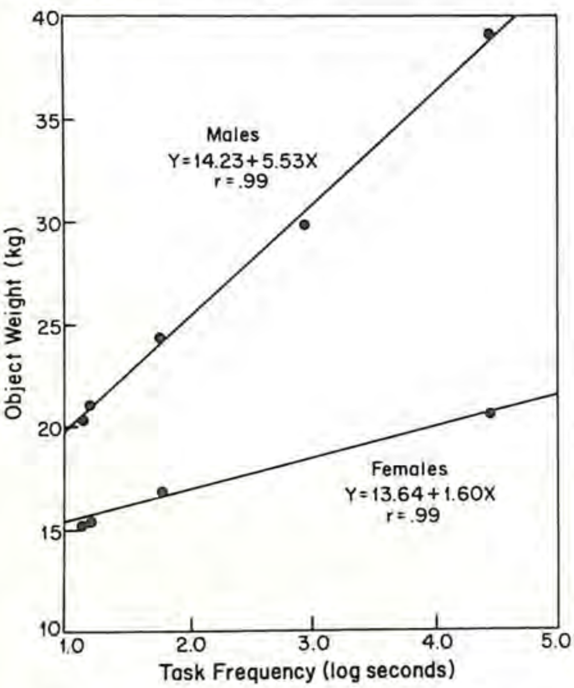

Figure 1. Mean results from low-lifting experiments.

Psychophysical studies of low lifting have also been conducted at Texas Tech University by Ayoub et al. (1976). Using a task frequency of 15 sec, Ayoub and his associates obtained means of 24 kg from male subjects and 15 kg from female subjects. The female results are in close agreement with Liberty Mutual data; however, the male results are somewhat higher. The male subjects may well have over-estimated since they were students who received only one trial with no prior training or conditioning. Similar procedures used in the early U.S. Air Force studies also resulted in high values (Emanuel et al., 1956; Switzer, 1962).

The effects of subject age and environmental heat stress on low lifting tasks have been investigated at Liberty Mutual (Snook, 1971; Snook and Ciriello, 1974b). There were no significant age differences within the ages tested (25 to 60 yr). However, environmental heat stress did have a significant effect ($p < .01$). Results from a repetitive low lifting task were 20% lower during a wet bulb globe temperature (WBGT) of 27.0°C than during a WBGT of 17.2°C.

Object size has been investigated by the U.S. Air Force with a psychophysical technique. McConville and Hertzberg (1966) conducted a study of one-handed low lifting and found that object weight varied linearly, but inversely, with the width of the object. Preliminary results from a current Liberty Mutual experiment indicate a similar, but considerably smaller, inverse relationship between object weight and object size (Ciriello and Snook, 1978).

FUTURE STANDARDS

If the development of standards were left up to scientists, there would not be very many—because scientists are perfectionists who never have enough data for an acceptable standard. However, if standards development were left up to the politicians, there would be too many—many of them unacceptable and unworkable. There is good reason to fear the latter if the scientific community does not take the initiative. The ideal approach is to design all manual handling tasks to fit 90% of the population. To begin with, however, a more conservative approach is necessary. The goal is to develop a standard that industry can live with, and yet a standard that will prevent the excessive and abusive exposures that do exist.

A conservative standard would be based upon male data and would consider individual differences. Based upon the currently available psychophysical data discussed in the previous section, a three-zone type of standard is suggested and illustrated in Figure 2. Zone 1 represents the weights that over 90% of the male industrial population can handle without overexertion or excessive fatigue. There would be no restrictions in this zone. Zone 2 represents the weights that 90% to 10% of the male population can handle without overexertion or excessive fatigue. Some of the workers can handle these weights, and some cannot. This zone might be considered as a "work practices" zone where the weights are permissible if the employer can show that workers have been selected for the job by some reasonable selection criteria (e.g., medical examination, strength testing, anthropometric measurements). Zone 3 represents the weights that less than 10% of the male population can handle without overexertion or excessive fatigue. No one should be required to lift weights in this zone.

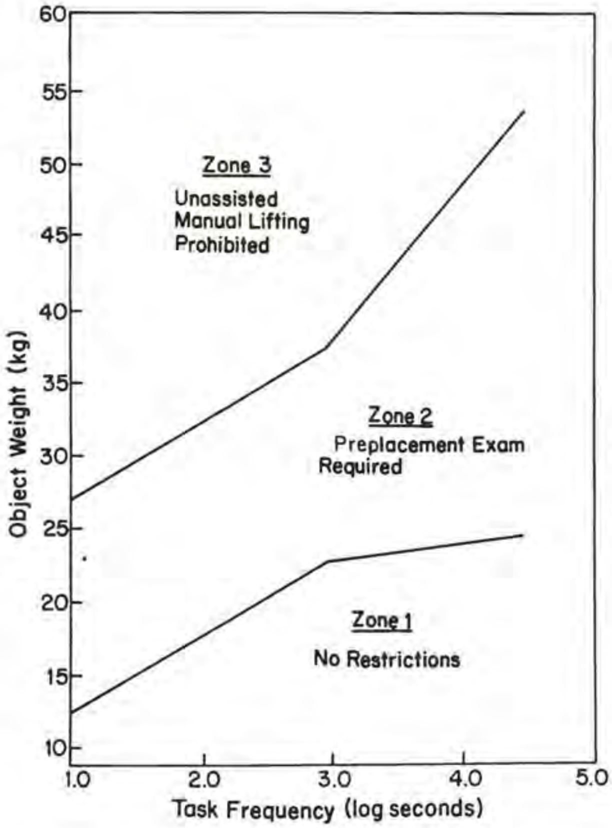

Figure 2. Proposed standard for manual lifting by a single individual.

The specific values for the boundaries separating the three zones (called the Zone 2 boundaries) are found in Table 2 as a function of the number of lifts required in an 8-hr working day. The proposal becomes even more conservative when one considers that these values are based upon lifting compact objects at a low height, and that lifting tasks are assumed to be evenly spaced throughout the working day. Consider also that this proposal would apply only to what workers are required to lift—not to what they voluntarily lift.

As more data are collected, separate standards can be developed for males and females, for compact and bulky objects, and for different types of manual handling tasks. The important point is to begin with the data that presently exist. The cost and suffering associated with lower back pain do not permit any delay.

Table 2. Zone 2 boundaries based upon 10% and 90% of male workers.

Lifts/day	*kg*	*Lifts/day*	*kg*
1	25 - 54	51	22 - 37
2	24 - 51	52	22 - 37
3	24 - 49	53	22 - 37
4	24 - 47	54	22 - 37
5	24 - 46	55	22 - 37
6	24 - 46	56	22 - 36
7	24 - 45	57	22 - 36
8	24 - 44	58	22 - 36
9	24 - 44	59	22 - 36
10	24 - 43	60	22 - 36
11	24 - 43	61	22 - 36
12	24 - 43	62	22 - 36
13	24 - 42	63	22 - 36
14	24 - 42	64	22 - 36
15	24 - 42	65	22 - 36
16	24 - 41	66	22 - 36
17	24 - 41	67	22 - 36
18	24 - 41	68	22 - 36
19	24 - 40	69	22 - 36
20	24 - 40	70	21 - 36
21	23 - 40	71	21 - 36
22	23 - 40	72	21 - 36
23	23 - 40	73	21 - 36
24	23 - 39	74	21 - 36
25	23 - 39	75	21 - 36
26	23 - 39	76	21 - 36
27	23 - 39	77	21 - 36
28	23 - 39	78	21 - 36
29	23 - 39	79	21 - 36
30	23 - 38	80	21 - 36
31	23 - 38	81	21 - 36
32	23 - 38	82	21 - 36
33	23 - 38	83	21 - 36
34	23 - 38	84-104	21 - 35
35	23 - 38	105-126	20 - 35
36	23 - 38	127-158	20 - 34
37	23 - 37	159-191	19 - 34
38	23 - 37	192-240	19 - 33
39	23 - 37	241-290	18 - 33
40	23 - 37	291-364	18 - 32
41	23 - 37	365-440	17 - 32
42	23 - 37	441-552	17 - 31
43	23 - 37	553-668	16 - 31
44	23 - 37	669-837	16 - 30
45	23 - 37	838-1013	15 - 30
46	22 - 37	1014-1269	15 - 29
47	22 - 37	1270-1536	14 - 29
48	22 - 37	1537-1923	14 - 28
49	22 - 37	1924-2329	13 - 28
50	22 - 37	2330-2500	13 - 27

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CHAPTER 2. SUMMARY

It is evident that what started out as a review of known areas became, in practice, a forum for new ideas and research suggestions. Troup's point that we do not have enough correlation between medically observed and laboratory simulated fractures of vertebrae is well taken. It may be that more detailed and comprehensive biomechanical models are required before the parameters are available for realistic input to the simulations of vertebral and associated tissue damage.

Similarly, Davis and Stubbs go on from the rationale for measurement of intra-abdominal pressure to a complete scheme for determining standards for manual materials handling. This study includes comprehensive laboratory measurement for mapping forces exerted onto intra-abdominal pressures and also a validation of features of the daily pressure records against injury data. With extension to other populations, this could be a very effective way of attacking the standard-setting problem directly.

Kroemer's report of standard methods of static-strength testing now needs extending to the complex world of dynamic strength. Also, as both he and Drury and Spitz point out, a reappraisal of static-strength testing is needed. Are there conditions in which predictions of maximum voluntary strength from the strength/duration curve would be preferable? It is interesting that maximum voluntary strength is essentially a psychophysical measure of how much pain the subject is willing to tolerate rather than how much the subject is able to tolerate in any damage-risk sense. It is also interesting that these limiting subsystems do interact considerably as evidenced by cardiovascular effects of sustained muscle contractions.

In practice, as Rodgers shows, oxygen uptake is sensed and self-regulated in a psychophysical manner. Jobs may differ and people may differ, but rarely does the worker utilize more than about 40% to 50% of maximum oxygen uptake. Her assertion is that we are not ready to predict the metabolic demands of a task from a synthesis of the demands of its constituent parts, nor are we ready to predict maximum aerobic capacity from other measures of the worker.

The value of 40% to 50% of maximum oxygen uptake again reappears in Lind and Petrofsky's experimental data. Here it seems to be the limit for steady state response of respiratory and circulatory parameters as well as arterial lactate levels. Promising, too, is the technique of measuring isometric endurance in different muscle groups after work to show their relative state of fatigue. The dynamic strength of arm muscles appears to be particularly critical for this type of repetitive work.

Self-knowledge of stress and self-regulation of workload and effort have been turned into a reliable procedure by Snook and his co-workers at Liberty Mutual with cross validation by Ayoub and his group at Texas Tech. Much of their work, not covered in Snook's paper, is reviewed later by Burse in this volume. Carlson, Drury, and Webber (1977) have also found that human beings have considerable precision in a lifted weight discrimination task with difference thresholds of about 4% of the weight handled. But the precision and reliability of a methodology alone are no guarantee that it is measuring anything relevant to manual materials handling safety. Fortunately, we have a number of cross validations. A small but clear example is in the voluntary endurance for lifting boxes of different sizes and weights (Drury, 1975). Here, subjects behaved precisely as if they were perceiving equal moments about the lumbar spine. On a grander scale, data from Herrin's epidemiological studies and Davis and Stubbs' field experiments are showing the same range of weight values that Snook has been measuring using psychophysics. When one considers the care with which Snook has checked his workloads and methods against a range of industrial jobs at each stage (not reported in his paper here), this agreement appears to be more than just fortuitous.

Examples have been presented of the more common "limiting subsystems" in manual materials handling tasks. It is not an exhaustive list (e.g., human thermoregulatory mechanisms, nutritional balance, or water balance could all be limiting under special conditions). Nor are these subsystems independent as becomes evident on reading the papers. But they do form, as the earlier NIOSH report showed, one dimension of a classification scheme for the research literature. The wide range of their criteria go some way in explaining the confusion caused by different researchers making wildly different practical recommendations on the basis of their experiments. With considerable care in experimentation and a thorough knowledge of the complexities of both worker and task, recommendations begin to converge. The day may even come when we can formulate the manual materials handling safety problem as an optimization, subject to a number of interdependent constraints following M. A. Ayoub's work. But that is the subject of later chapters.

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CHAPTER 3

MODELS OF HUMAN PERFORMANCE

INTRODUCTION

Science can be said to be the search for constants, for new ways of looking at the world so that it appears orderly rather than chaotic. These "ways of looking" are the theories of science and are models of nature. Models typically start by describing the results of one study, but at this level they are too specific to be of great value. Any data analysis, such as statistical testing, implies a model because it makes testable assumptions about the data on which the analysis is based. Again, these are often too simple; knowing that a variable is normally distributed in a population is some help, but not much, in removing the chaos. Most models attempt to go beyond mere statistical properties of data to examine relationships that could be expected from the "structure" of the situation. This structure has been a challenge to philosophers for hundreds of years because it is not wholly objective. The great minds of science are the ones who change our viewpoint of the structure and see radically new ways of progress.

At a practical level, a model is as good as the quality and range of its predictions. The more of the chaos it renders orderly, the more useful it is. Although, as the saying has it, there is nothing as practical as a good theory, this practicality is not the whole story. The biomechanical models that form the bulk of this chapter should not be judged merely on how many real-world materials handling problems they solve.

Biomechanics rests on an analogy between man and machine that is simple to state, but that can be most complex to analyze. The progressive refinement in this model of man as a system of joints and levers is well illustrated in the papers in this chapter. The short history in Ayoub and El-Bassoussi's paper in this chapter is an example of the growth of a field of modeling. Parallel to this growth is the progression of models in the following papers. The model used by Fish in a typical application paper has all the limitations the author states so clearly. It is a static model in that accelerations and inertias of the body parts are not taken into account in the calculations. It is limited to the sagittal plane—no twists and rotations are allowed. It removes most of the effect of intra-abdominal pressure in relieving spinal forces by instructions to the subjects. Despite these limitations, valid and important results are obtained. More pointedly, it represents a prototype of the level of investigation that should be possible in even the most traditional methods study department in industry.

Two restrictions on the simple model are removed by the Schultz, Liu, and Novak paper. Here, an approach between anatomy and mechanics is used to obtain a more detailed model of the internal force distribution in the lower trunk during lifting and of other manual materials handling tasks. Also, the strict requirement of sagittal symmetry is lifted to allow more complex forces within the lower trunk. Although it is still in its early stages, this model appears to be getting down to one of the major areas implicated by the injury data.

Chaffin's review of the University of Michigan's longstanding modeling effort shows the same generalizations of the static model as the previous paper. Now, however, restrictions imposed by the individual subject's maximum muscular forces or torques are added. The packaging together of this advanced modeling effort with a unique data base in a convenient computer routine has helped to change occupational biomechanics into a numerically predictive tool with a long list of validated applications.

With the restriction to static models removed, the sheer complexity of the model solution techniques increases greatly. To be at all tractable at this stage, Ayoub and El-Bassoussi's dynamic model has to assume sagittal plane motions although a realistic model of intra-abdominal pressure is included. By now, the model generates its own movement path from a starting to a final position rather than needing data supplied by photographs or other input data.

The approach to dynamic modeling by Muth, Ayoub, and Gruver is really very different. Despite all of its simplifications and assumptions, it represents a definite attempt at normative modeling. It shows how a "rational" body would behave if it were trying to optimize some measure of work load. In effect, it predicts the path of a lift that is, in some sense, the "best" lift.

Goldman's modeling paper leaves the biomechanical field (although not entirely) to review the interrelationships between human capacity, task, and workload as seen in materials handling tasks. He shows how not just forces and pressures need to be predicted but metabolic cost, heart rate, and perceived exertion. It would seem an obvious next step to use the dynamic biomechanical models to estimate metabolic costs. With the Givoni and Goldman equations to predict heart rate and rectal temperature from metabolic cost and Borg's relationship between work load and perceived exertion, we should be approaching a science of manual work, a model that orders a significant part of the current chaos.

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PRACTICAL MEASUREMENT OF HUMAN POSTURES AND FORCES IN LIFTING

D. R. Fish

INTRODUCTION

Physical therapists evaluate and treat a large number of patients suffering from low back pain. Since lifting activities are sometimes implicated in the etiology or aggravation of low back pain, most treatment programs for these patients include instruction in the "proper" way to lift. Unfortunately, however, the efficacy of the time honored straight-back/bent-knee method of lifting for relief of pain or improvement of function has not been well documented. The purpose of the present study was, therefore, to calculate and compare the forces induced at the level of the L4/5 intervertebral disc during straight-back/bent-knee (SB/BK) and flexed-back/straight-knee (FB/SK) lifts.

METHOD

To minimize anthropometric variations in this study, four normal adult males of similar height and weight were selected. The subjects ranged in height from 183 to 189 cm and weighed approximately 72 to 79 kg. After the subject's height and total body weight had been determined, additional anthropometric data were collected in preparation for film analysis. First, the weights of appropriate extremity segments were determined according to the immersion technique described by O'Connell and Gardner (1972). This involved the systematic immersion of each segment into an overflow tank and the subsequent weighing of each volume of displaced water. The actual weight of each extremity segment was then estimated by multiplying the weight of the displaced water by the specific gravity of the extremity segment, which was drawn from data reported by Dempster (1955). The weight of the head and neck segment was estimated on the basis of Dempster's finding that this segment represents approximately 7.9% of the total body weight. The weight of the trunk from the level of the 7th cervical vertebra down to the level of the L4/5 intervertebral disc was estimated after subtracting the weights of all extremity segments and the weight of the head/neck segment from the total body weight.

After the anthropometric data had been collected, the subject was prepared for the filming process. Skin markers were used to facilitate recognition of joint axes at the right hip, glenoid fossa, elbow, and wrist, and marker fins were applied to the skin overlying the spinous processes of the 1st lumbar and 7th cervical vertebrae to facilitate estimation of vertebral levels. The subject was then positioned in such a way that a direct lateral view of his right side could be filmed throughout the lifting activities.

Two weight assemblies were constructed for use during the lifting activities. The heavier (20 kg) assembly was essentially a dumbell with weights positioned centrally so that the two ends of the steel bar could be grasped. The linear dimensions of the lighter (0.2 kg) assembly matched those of the heavier assembly.

The experimental design required that each subject perform the following lifts:

1. SB/BK lift of 20 kg from floor to height of approximately 1.25 m (height of elbows when standing erect).
2. FB/SK lift of 20 kg from floor to elbow height.
3. FB/SK "control" lift of 0.2 kg from floor to elbow height.

A load of 20 kg was selected since this is a "reasonable" weight, and apparently represents a comfortable stress level for most adult males according to psychophysiological data reported by Snook and Irvine (1967) and Snook, Irvine, and Bass (1970).

To learn the three lifts, each subject read the instructions and observed a demonstration of these lifts. In a brief practice session, the subject was encouraged to bear weight equally on both feet, approximate a steady lift velocity, and exhale slowly during each lift. For the SB/BK lift, subjects were told to begin in the erect standing position; flex at hips and knees, attempting to maintain a near-vertical trunk position; grasp the 20-kg weight assembly in such a way that your elbows are lateral to your knees; lift by straightening your knees, still keeping your trunk near vertical; and hold the 20-kg weight as close to your body as possible (Figure 1). Two FB/SK lifts were performed; one entailed lifting a 20-kg weight assembly and the other required lifting only 0.2 kg (Figure 2). The specific instructions for these FB/SK lifts were to begin in the erect standing position; bend forward, flexing your hips but keeping your knees straight; and lift by "straightening up."

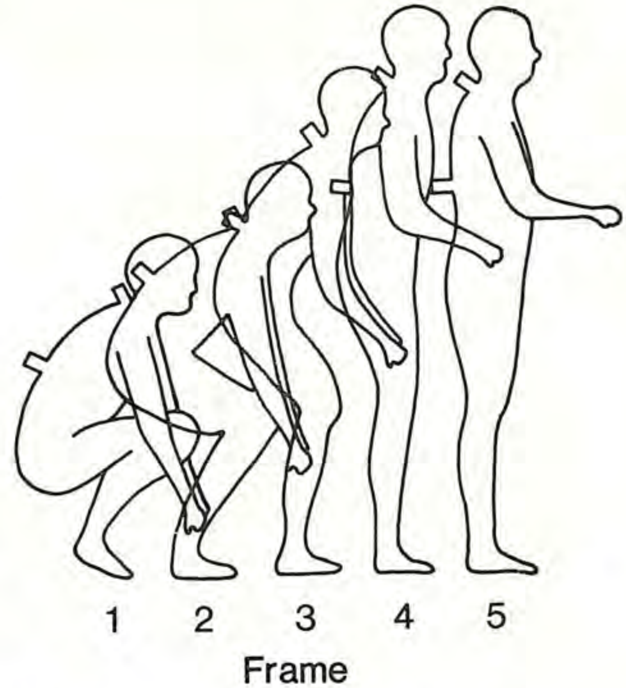

Figure 1. Straight-back/bent-knee lift.

A Bolex Rex H16 spring-wound movie camera with a wide angle lens was set on a tripod about 5 m from the subject. To provide an accurate time record, a beam splitter described by O'Connell (1968) was placed in front of the camera lens to allow the image of a timer dial to be superimposed over the figure of the performing subject. With the film speed set at 32 frames/sec, analysis of every frame of film exposed during the lift sequences was considered impractical; so 5 representative frames were selected by establishing equal time intervals between the initiation and completion of each lift.

After the filming process was completed and representative frames had been selected, each frame was analyzed to determine the total "task torque" acting at the level of the L4/5 disc. The total task torque was estimated by adding the task torques generated by the hand-held weight and every body segment cephalad to the L4/5 disc. Since the weight of each segment was previously estimated, the only new information required to complete this calculation was the center of gravity of each segment; this was estimated using Walton's template for segmental centers of gravity (Walton, 1970). The spatial relationships of the various segments were offered by the film itself as the image was projected onto graph paper.

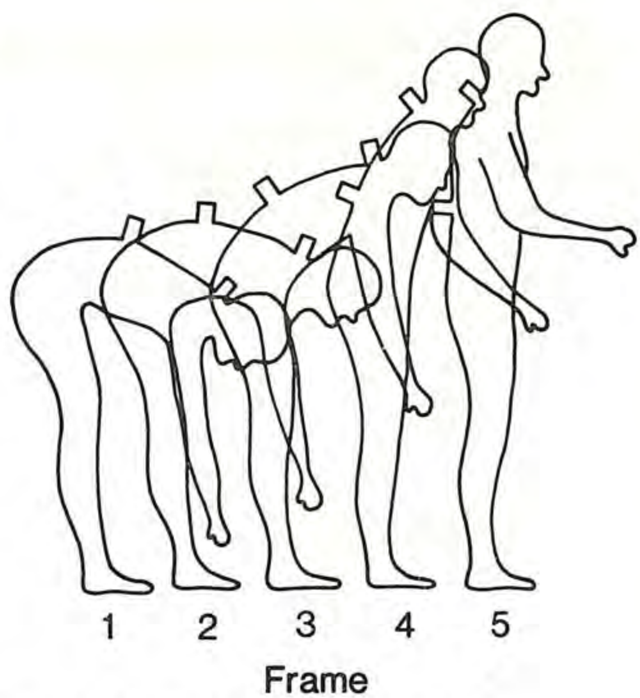

Figure 2. Flexed-back/straight-knee lift.

The results were ultimately derived by mathematical extensions of the task torque data. The literature indicates that the moment arm of the lumbar erector spinae is about 50 mm (Chaffin, 1973; Bartelink, 1957). With this knowledge and the use of static equilibrium equations, the rotational (or extension) component of the erector spinae muscle force can be determined. Under static equilibrium conditions, the task torque, i.e., the torque generated by the hand-held weight and the body segments cephalad to the L4/5 disc, is exactly offset by the "reactive torque," which is primarily generated by the lumbar erector spinae.

$$\text{Task torque} = \text{Reactive torque}$$
$$\text{Task torque} = (F_{es})(MA_{es})$$
$$\text{Task torque} = (F_{es})(50\text{ mm})$$
$$F_{es} = \frac{\text{Task torque}}{(50\text{ mm})}$$

There is a direct, positive relationship between the muscle force in the lumbar erector spinae and the force of compression at the intervertebral discs. An estimate of this compression force was made in accordance with the mathematical process described by Morris, Lucas, and Bresler (1961). Figure 3 illustrates the factors involved in the calculation of disc compression forces. Under static equilibrium conditions the sum of the vertical force components acting at the L4/5 disc must equal zero:

$$\Sigma V = 0$$
$$F_{sw} + F_{es}(\cos\alpha) - R(\cos\beta) = 0$$
$$R(\cos\beta) = F_{sw} + F_{es}(\cos\alpha) \qquad (1)$$

Similarly, the sum of the horizontal forces acting at the disc must equal zero:

$$\Sigma H = 0$$
$$R(\sin\beta) - F_{es}(\sin\alpha) = 0$$
$$R(\sin\beta) = F_{es}(\sin\alpha) \qquad (2)$$

By dividing Equation 2 by Equation 1, the value of tan β and thus the angle β can be determined:

$$\frac{R(\sin\beta)}{R(\cos\beta)} = \tan\beta = \frac{F_{es}(\sin\alpha)}{F_{sw} + F_{es}(\cos\alpha)}$$

In the final step, the reactive (compression) force at the disc (R) is determined:

$$R = \frac{F_{es}(\sin\alpha)}{\sin\beta}$$

In the actual process of calculating these values, the direction of pull of the erector spinae was estimated on the film tracings and was assumed to be vertical in the lift completion postures.

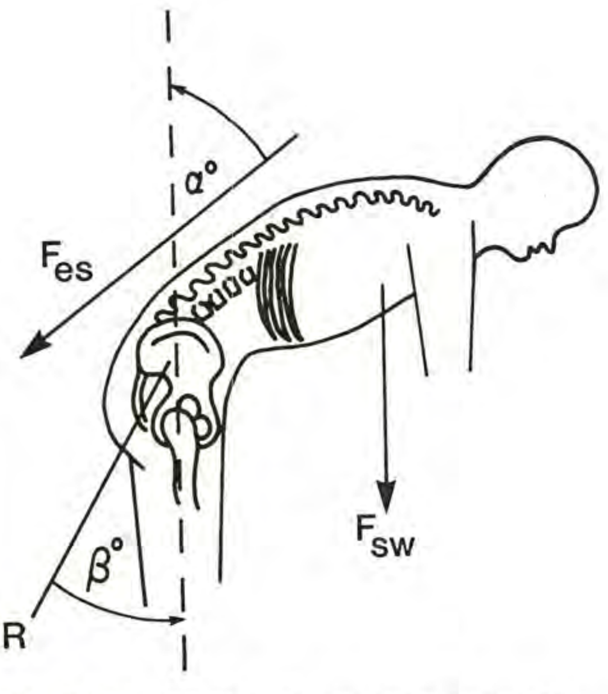

Figure 3. Diagram of disc compression factors (adapted from Morris, Lucas, and Bresler, 1961).

where: F_{sw} = the gravitational force acting on the system weight
F_{es} = the effective joint rotational force of the erector spinae
R = the "reactive force" at the L4/5 disc (i.e., compression force)
α = the angle that the erector spinae action line makes with the vertical
β = the angle that the reactive force vector makes with the vertical

RESULTS

A *t-test* for paired data was performed to test for significance of the difference between the mean values associated with the FB/SK and SB/BK lifting of 20 kg; a similar analysis was performed to test for significance of the difference between the mean values associated with the FB/SK lifting of 20 kg and 0.2 kg.

The obvious hypothesis that the FB/SK lifting of a 20-kg load would be associated with significantly higher erector spinae muscle forces and disc compression forces than the similar lifting of a 0.2-kg load was substantiated in all subjects at all frames (Tables 1 and 2). (See also Figures 4 and 5.)

Table 1. Mean rotational (extension) component of erector spinae muscle force (kg).

Frame	*SB/BK-20**	*FB/SK-20†*	*FB/SK-0.2‡*	*p*
1	392	415		NS§
2	416	393		NS
3	383	384		NS
4	265	351		NS
5	212	232		NS
1		415	234	<.003
2		393	254	<.001
4		384	231	<.014
3		351	153	<.001
5		232	75	<.004

*Straight-back/bent-knee lift of a 20-kg load.
†Flexed-back/straight-knee lift of a 20-kg load.
‡Flexed-back/straight-knee lift of a 0.2-kg load.
§Not significant.

Table 2. Mean compression force at the L4/5 disc (kg).

Frame	*SB/BK-20**	*FB/SK-20†*	*FB/SK-0.2‡*	*p*
1	450	433		NS§
2	478	421		<.001
3	451	434		NS
4	326	410		NS
5	273	294		NS
1		433	246	<.003
2		421	274	<.001
3		434	265	<.012
4		410	192	<.001
5		294	116	<.003

*Straight-back/bent-knee lift of a 20-kg load.
†Flexed-back/straight-knee lift of a 20-kg load.
‡Flexed-back/straight-knee lift of a 0.2-kg load.
§Not significant.

The hypothesis that the FB/SK method would require greater muscle forces in the lumbar erector spinae than would the SB/BK method when lifting 20 kg was rejected since no significant difference was found between the mean F_{es} values associated with these lifts (Table 1). (See also Figure 4.)

The hypothesis that the FB/SK lifting of 20 kg would induce greater compression forces at the L4/5 disc than the SB/BK lifting of the same load was also rejected. At frame 2, the mean compression force induced by the SB/BK lift was significantly greater than that induced by the FB/SK lift ($p < 0.001$) (Table 2). (See also Figure 5.) When the postures assumed by each subject at frame 2 of the SB/BK lift were reviewed, it was evident that these corresponded to the phase at which the weight assembly was pushed forward to clear the knees. Apparently, the higher task torque resulting from this action coupled with the more vertical trunk position associated with the SB/BK method of lifting accounts for the significantly greater disc compression force associated with the SB/BK lift at frame

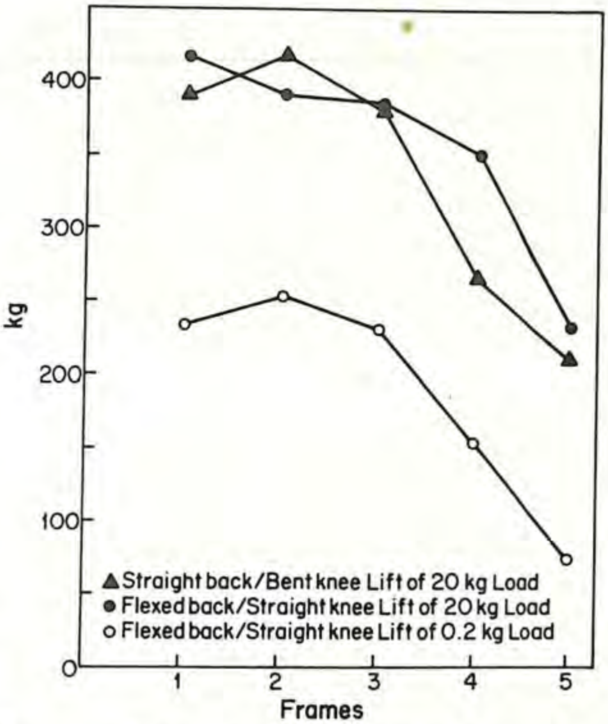

Figure 4. Mean F_{es} values (rotational component of erector spinae total muscle force).

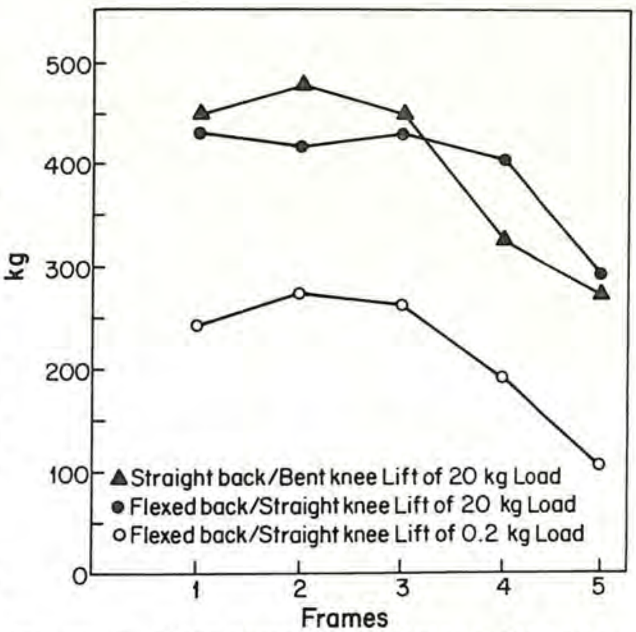

Figure 5. Mean compression forces at the L4/L5 disc.

2. Certainly, any circumstance that requires an increase in the horizontal distance between the trunk and the hand-held weight will increase the task torque and the subsequent low back stress. Conversely, decreasing the horizontal distance between the trunk and the hand-held load will reduce the task torque and its associated stress factors. Thus, the SB/BK lifting of an object that is small enough to be brought up between the knees should be much more efficient than the SB/BK lifting of an object that must be pushed forward to clear the knees as was required in this study (Park and Chaffin, 1973).

DISCUSSION

It should be emphasized that in this study a highly simplified static mechanical model was applied to a complex biomechanical system. The calculations were based on static equilibrium equations that disregard the effect of the initial acceleration against gravity. It has been estimated that a 13.6 kg-load would give an effective resistance of 15.7 kg during the acceleration phase of lifting (Park and Chaffin, 1973); the frame 1 task torques in this study are therefore likely to be underestimated by a similar factor.

The literature indicates that intra-abdominal pressure may contribute to the stabilization of the spine during lifting activities (Bartelink, 1957; Morris, Lucas and Bresler, 1961; Asmussen and Poulsen, 1968). However, since the magnitude of this contribution is a matter of considerable controversy, this factor was minimized by instructing the subjects to exhale during the lifts and was eliminated from the calculations performed in his study.

Because information on the center of gravity of that portion of the trunk between the levels of the L4/5 disc and the spinous process of C7 was not found in the literature, the center of gravity of this trunk segment was assumed to lie at the midpoint between these two levels. Any assumption regarding the center of gravity of the trunk may be invalidated by actual shifts in the center of gravity that may occur with inspiration and expiration.

Unless the subjects participating in the study have anthropometric characteristics that approach the mean values determined in Dempster's study of eight cadavers (1955), a systematic error may be introduced in the calculation of segmental weights and centers of gravity. Although this potential source of error must be considered, Dempster's data were selected over other data, such as those reported by Clauser et al. (1969), because Walton's (1970) template was designed in accordance with Dempster's data, and Walton's template is a valuable time-saving tool for estimating segmental centers of gravity by film analysis.

The distributed muscle force of the erector spinae is treated as a single resultant force acting on a moment arm of 50 mm. This may be considered as a reasonable estimate of reality although LeVeau (1974) has shown that the axis of rotation at the intervertebral disc is not constant and indeed sometimes lies outside the disc.

The calculations do not account for the portion of the tensile "muscle" force that may actually be borne by posterior spinal ligaments as suggested by Grieve (1974) and Floyd and Silver (1955).

A precise kinematic analysis was not performed so there is no documentation of the accuracy with which the subjects adhered to the lifting instructions. The reader must therefore assume that the consistent starting positions, the instructions, and the practice sessions were sufficient to standardize the lifts.

In spite of the limitations and problems cited above, the results are compatible with those found in the literature. Park and Chaffin (1973) reported that the SB/BK method of lifting increased the force of compression on the lumbosacral disc by over 50% of that incurred by the FB/SK method under certain conditions; interestingly, the conditions cited, i.e., a load of 15.7 kg placed 20 in. from the ankle and 10 in. from the floor, are similar to those associated with frame 2 postures in the present study. Further, Park and Chaffin estimated the disc compression forces to be 242.6 kg and 331.1 kg under the specific conditions outlined above. The relative magnitudes of these forces are reasonably consistent with those calculated in the present study. A reasonable positive correlation is also seen with data reported by Nachemson (1965). In a direct (in vivo) study of intradiscal pressures, Nachemson estimated that compressive forces of 250 to 340 kg resulted when subjects held 10 kg in each hand and leaned forward 20°.

CONCLUSIONS

The small sample and specific conditions used in this study indicate the necessity for caution in making generalizations from the data reported. However, the results do suggest that the SB/BK method of lifting is not always less stressful than the FB/SK method when stress is defined in terms of the muscle forces required in the lumbar extensors and the magnitude of the compression forces induced at the L4/5 intervertebral disc. The method of film analysis used has merit in that it requires a minimum of equipment and provides an accurate kinematic record. It should be within the capability of many industrial organizations to perform similar studies, under qualified guidance, to answer specific manual materials handling problems.

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A SCHEME FOR ANALYSIS OF THE MECHANICS OF THE LOWER TRUCK DURING MANUAL MATERIALS HANDLING

A. B. Schultz, W. K. Liu, and G. J. Novak

INTRODUCTION

Back injury is a subject about which much has been said but little has been established scientifically. There seems to be general agreement that mechanical factors are involved in back injuries, but this has not been proven. Nevertheless, it appears that a stronger case can be made for the significance of mechanical factors than for any other kind of factors. The clinical evidence for this claim has been outlined by Nachemson (1971), and Chaffin and Park (1973) have begun to establish the claim epidemiologically. Moreover, of the 8 million spine impairments found by the U.S. Public Health Service (1973), nearly 700,000 are reported to have resulted from a "one-time lifting or exertion."

A basic understanding of the mechanics of the trunk would be useful in determining how back injuries might be avoided, but surprisingly little attention has been paid to the biomechanics of activities presumed sometimes to lead to back injury. A research program aimed generally at arriving at a better understanding of trunk mechanics during the execution of manual materials handling tasks has recently been undertaken as a joint project between the Department of Materials Engineering at the University of Illinois, Chicago Circle, and the Department of Orthopaedics at Rush Medical University, Chicago, Illinois. The program is under the sponsorship of the National Institute for Occupational Safety and Health. Several different approaches to gaining better understanding of the mechanics of back injury are being taken. This paper, which considers only one of them, aims to determine what forces internal to the trunk in the low back region are generated in response to several different kinds of manual materials handling activities. It is an interim report concerning research techniques more than a presentation of results and conclusions.

METHODS

The determination of the internal lower trunk forces and moments that might be created during the execution of a handling task involves two basic steps: (1) determination of the net reaction across a section of the lower trunk; and (2) determination of internal force distributions that can supply this net reaction.

Determination of the Net Reaction

Imagine the body to be sectioned into two parts by the transverse plane passing through the L5/S1 intervertebral disc. The net reaction supplied by the inferior and acting on the superior section must, along with all external forces acting on the superior section, equilibrate that section under static conditions. The net reaction consists of the three components of the force vector and the three components of the moment vector that do this.

Manual materials handling tasks are often said to be executed "dynamically" because movement occurs. Usually the accelerations involved are small enough so that the inertial forces they generate may safely be neglected when compared with other forces. Such quasi-dynamic situations, from the point of view of mechanics, may be analyzed as if they were static. A discussion of truly dynamic conditions is beyond the scope of this presentation. It seems appropriate to obtain a much better understanding of the static situation than exists at present before attempting to take into account the additional complications of a dynamic analysis.

The problem of determining the net trunk reaction is straightforward, at least conceptually. In our laboratory experiments, we use the scheme illustrated by Figures 1-3. A subject grips the handles of an instrumented workpiece that measures the three components of the external force exerted on each of his hands (Figures 1 and 2). The handles of the workpiece are designed so that significant

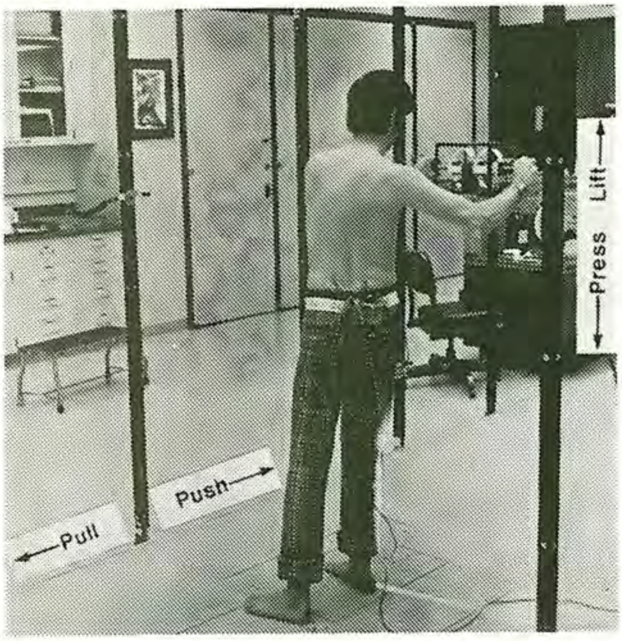

Figure 1. Subject executing typical task. The instrumented workpiece is at shoulder height, 142 cm above the floor, and the feet are placed in the right position. Bilateral EMG electrodes are affixed at the L3 level. (From Berkson et al. 1977.)

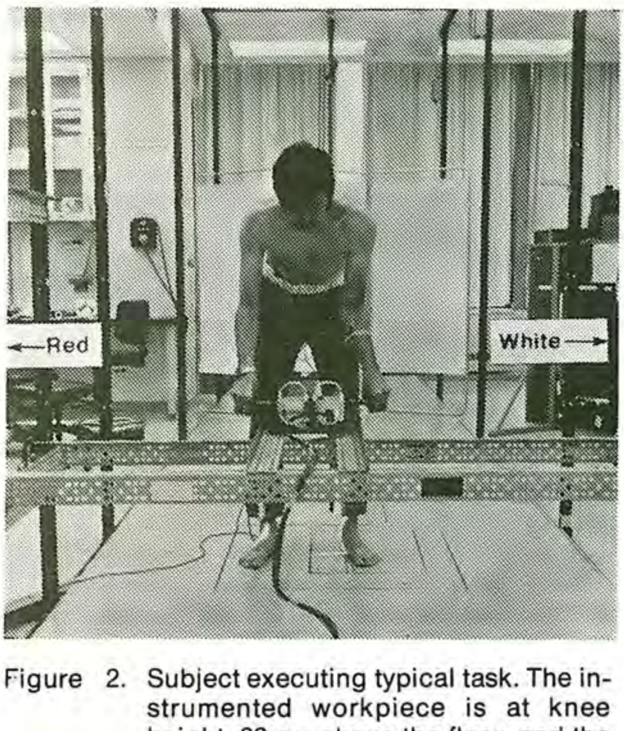

Figure 2. Subject executing typical task. The instrumented workpiece is at knee height, 60 cm above the floor, and the feet are placed in the anterior position. (From Berkson et al. 1977.)

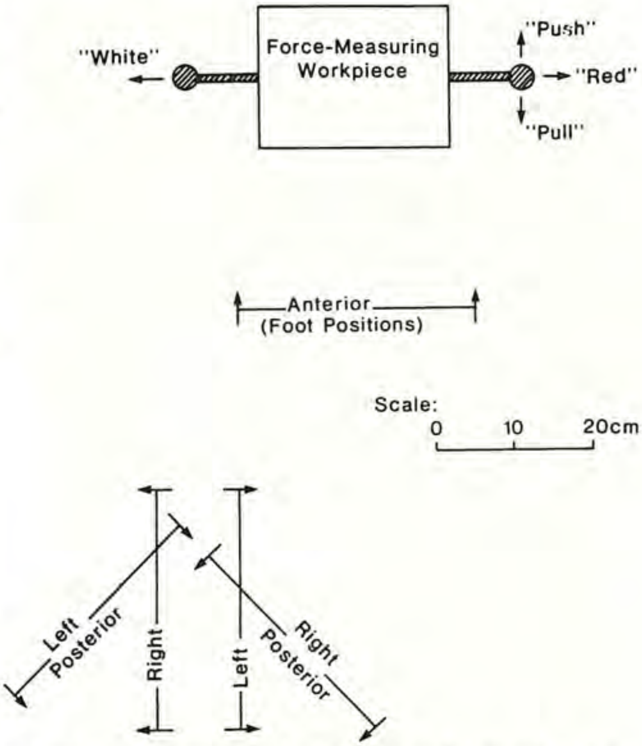

Figure 3. Positions of the feet relative to the workpiece. The drawing is to scale and is a view from above. The foot-position arrows show where the medial edges of the forefeet were placed in each of the five foot positions. The arrows show the directions in which the subjects faced. The hand-force directions in the plane parallel to the floor are also shown; lift and press forces were exerted vertically upward and downward, respectively. (From Berkson et al. 1977.)

reaction moments cannot be exerted. The workpiece may be placed anywhere within reach, and forces of any magnitude can be exerted upon it in any direction (Figure 3). While executing an assigned task, the subject is photographed from four mutually orthogonal views. A wide range of manual materials handling situations can be observed in this way.

The external forces acting on the imagined superior section of the body consist of the measured external forces exerted on the hands and the weights of the body segments included in the section. The data of Clauser et al. (1969) are used to apportion the subject's body weight to the various body segments. The data obtained from the configuration photographs are used to determine the locations of the mass centers of each segment involved.

The net reaction analysis is conducted proceeding proximally, segment by segment, from the workpiece. The known reaction at the distal end of each segment is compounded with the segment weight vector. Equilibrium equations are then solved to compute the reactions at the proximal end of the segment. In this way, the net reaction across each major joint in the body is calculated, with the configuration of all body parts taken into account. By proceeding from each of the hands to the shoulder and then to the lower trunk, the net lower trunk reaction is calculated through repeated application of the equations of equilibrium. Because the hand forces and the body segment weights are the only external forces acting on the upper body and they are known, the six equations of equilibrium can be used to calculate the six components of the net reaction exerted across the L5/S1 level transverse section.

Substantial calculation is required to compute the net reaction, but the use of digital computers makes this problem tractable. The most difficult task is to quantify the configuration so that the centers of mass of the body segments can be located. We are presently investigating the degree of accuracy necessary to locate these mass centers so that the true net trunk reaction is adequately approximated.

Determination of Possible Internal Force Distributions

Determining internal force distributions is conceptually much less straightforward than determing the net reaction. This is because many structures internal to the trunk may exert forces that are unknown and cannot easily be directly measured, whereas the requirement that the sums of the internal forces and moments must equal the net reaction components provides only six equations. Through use of some simplifying assumptions, however, reasonable estimates of the gross distributions of internal forces can be made.

For each activity studied, estimates of the internal force distribution of the trunk were made based on the net reaction computed as just outlined. Representative trunk cross-sectional dimensions were used. Longitudinally directed internal forces were considered to act on the vertebral column, in the posterior soft tissues of the back, and in the anterior and the right and left lateral abdominal walls. C, E, A, V_R, and V_L, respectively, denote these forces. A longitudinal abdominal pressure resultant, P, was assumed. Antero-posterior and lateral vertebral column shears as well as right and left side horizontal components of lateral abdominal wall forces (denoted S_P, S_L, H_R, and H_L, respectively) were also assumed for a total of 10 internal forces (Figure 4).

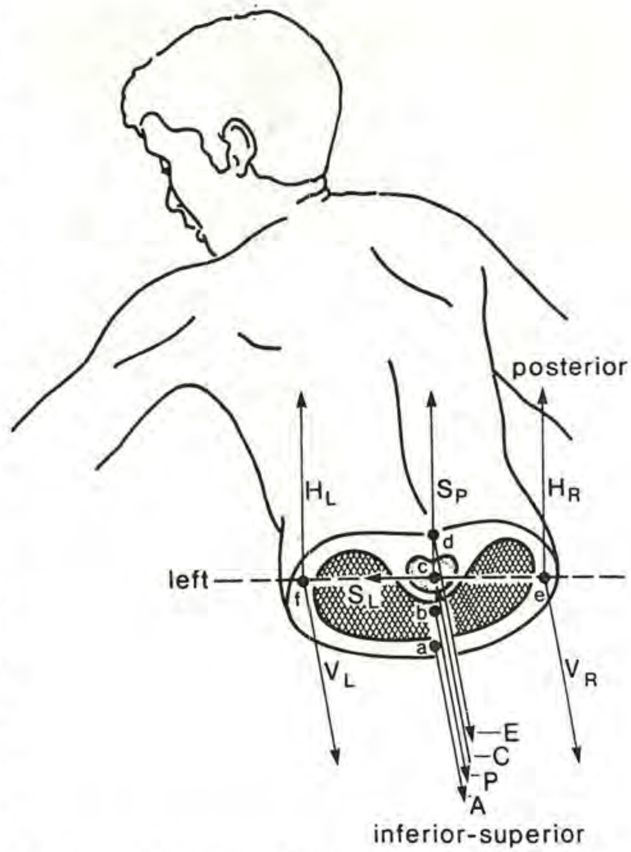

Figure 4. Assumed internal forces acting at the L5/S1 level. S_p originates at point C. Cross sectional dimensions used were: AC, 17 cm; BC, 11 cm; DC, 5 cm; EC = FC = 16 cm.

No antagonist activity was permitted in any structure, so that either E or A, V_L or V_R, and H_L or H_R were zero. By postulating pressure resultants P of 0, 500, or 1000N, the problem was reduced to one with six unknowns and so was determinate. For each activity and each abdominal pressure resultant, the six non-zero internal forces were computed, providing estimates of internal force distributions.

SAMPLE RESULTS AND DISCUSSION

To date, laboratory observations have been made on 29 normal male volunteers quasi-statically exerting lift, press, pull, and three push forces on the instrumented workpiece in two sagittally symmetric and six nonsymmetric basic body configurations (Figures 1-3). The forces were exerted by the left hand, the right hand, and both hands. Body configuration data were recorded as already outlined.

A typical set of estimates indicated:

1. With the workpiece at approximately shoulder height and $P = 0$, maximum forces for all exercises and configurations were of the order:

$E = 2800N$ $S_P = 300N$ V_L or $V_R = 1000N$
$C = 3100N$ $S_L = 200N$ H_L or $H_R = 300N$
$A = 700N$

2. With the workpiece at approximately knee height, these maxima became:

$E = 4700N$ $S_P = 700N$ V_L or $V_R = 1000N$
$C = 5200N$ $S_L = 300N$ H_L or $H_R = 1100N$
$A = 800N$

3. A non-zero value for P decreases E and C and increases A. It does not affect the other forces considered.

4. The E force had maximum value in two-handed, sagittally symmetric, knee-height lifts. It did not exceed 60% of this maximum in any shoulder height exercise or configuration. Body twisting reduced it further, especially for the push and pull exercise. In press exercises, it was usually zero.

Caution should be used in interpreting these numbers for several reasons. First, the analysis involves several assumptions whose validities have not yet been tested. Second, it is not yet known to what extent the group of volunteers represents the general population of normal male industrial workers. Third, the magnitudes of the internal forces reflect to a fair extent the magnitudes of the external forces voluntarily exerted. It is not yet known what factors limit these external forces; limitations on trunk component strengths may or may not have a role. Nevertheless, few estimates of trunk internal force magnitudes have been reported and the numbers arrived at in this study begin to provide an initial set of estimates for their values.

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BIOMECHANICAL MODELS OF HUMAN STRENGTH IN MANUAL MATERIALS HANDLING

D. B. Chaffin

When one is concerned with the occasional act of manually handling an object in industry, a principle human attribute to consider is that of the strength of the worker. As has been discussed, specific static strength attributes of a person can be gathered in a safe and reliable manner following the protocols suggested by Kroemer (1970), Caldwell et al. (1974), and Chaffin (1975b). The question then becomes, how are these data applied to a specific manual materials handling activity? It is the intent of this paper to discuss one approach to this question, namely, the development of computerized biomechanical strength models.

Computerized simulation models of the gross musculoskeletal system were first reported by Pearson et al. (1963) for arm motions, and by Plagenhoef (1963) for whole-body, sagittal plane motions. These models allowed the estimating of joint forces and torques resulting from momentum and gravity acting on the segmental body masses. In essence, these were computerizations of the body kinematics expressed earlier by Dempster (1955) and other functional anatomists. Placing a load in the hands during lifting simulations was added by Fisher (1967).

Chaffin and Baker (1970) were the first to add strength values to predict the maximum possible hand force (while in a given posture) for static sagittal plane activities. This approach was enlarged upon by Schanne (1972) to depict seated operator static strength predictions in three dimensions. More recently, Garg and Chaffin (1975) have further developed the Schanne model to predict both seated and standing operator static strengths. This last model perhaps holds the greatest promise because it has the flexibility to simulate the large number of extreme postures possible in industrial materials handling activities. The following describes this model and discusses some of its uses.

BIOMECHANICAL STRENGTH MODEL LOGIC AND DATA

Biomechanical strength models are based on a kinematic linkage representation of the human body. Figure 1 depicts this for the three dimensional model.

To manipulate the body posture, a set of angles (depicted in Figure 2) are inputted into the model. The size of the body links can be inputted with reference to anthropometric data suggested by Dempster and Gaughran (1967). Mass centers-of-gravity locations are estimated relative to the anthropometrically defined link lengths of Dempster and Gaughran. The mass of each link is based on the cadaver segment studies of both Dempster (1955) and Drillis et al. (1963).

Biomechanical strength modeling involves the comparison of maximum voluntary torques (VT) to the torques (RT, called "resultant torques") resulting from the forces acting at the hands, body segment weights, and any external constraints. Maximum voluntary torques, representing the strength of the subject and, therefore, required as input to the model, are calculated from data gathered on carefully controlled and dimensioned test equipment. A person's voluntary strength (often referred to as "reactive torques") depends on a number of factors. Major among these are body position; individual characteristics such as health, prior training, sex, age; motivation; and level of fatigue at the time of exertion.

Muscles react to an externally applied force by "pulling" across articulations. The ability of a muscle to produce a torque varies with the included angles of the joints across which it is pulling. For example, the lower arm is stronger (i.e., has a higher maximum voluntary reactive torque) in lifting when the included angle at the elbow is 90° than when it is 180° or extended (Clarke, 1966; Schanne,

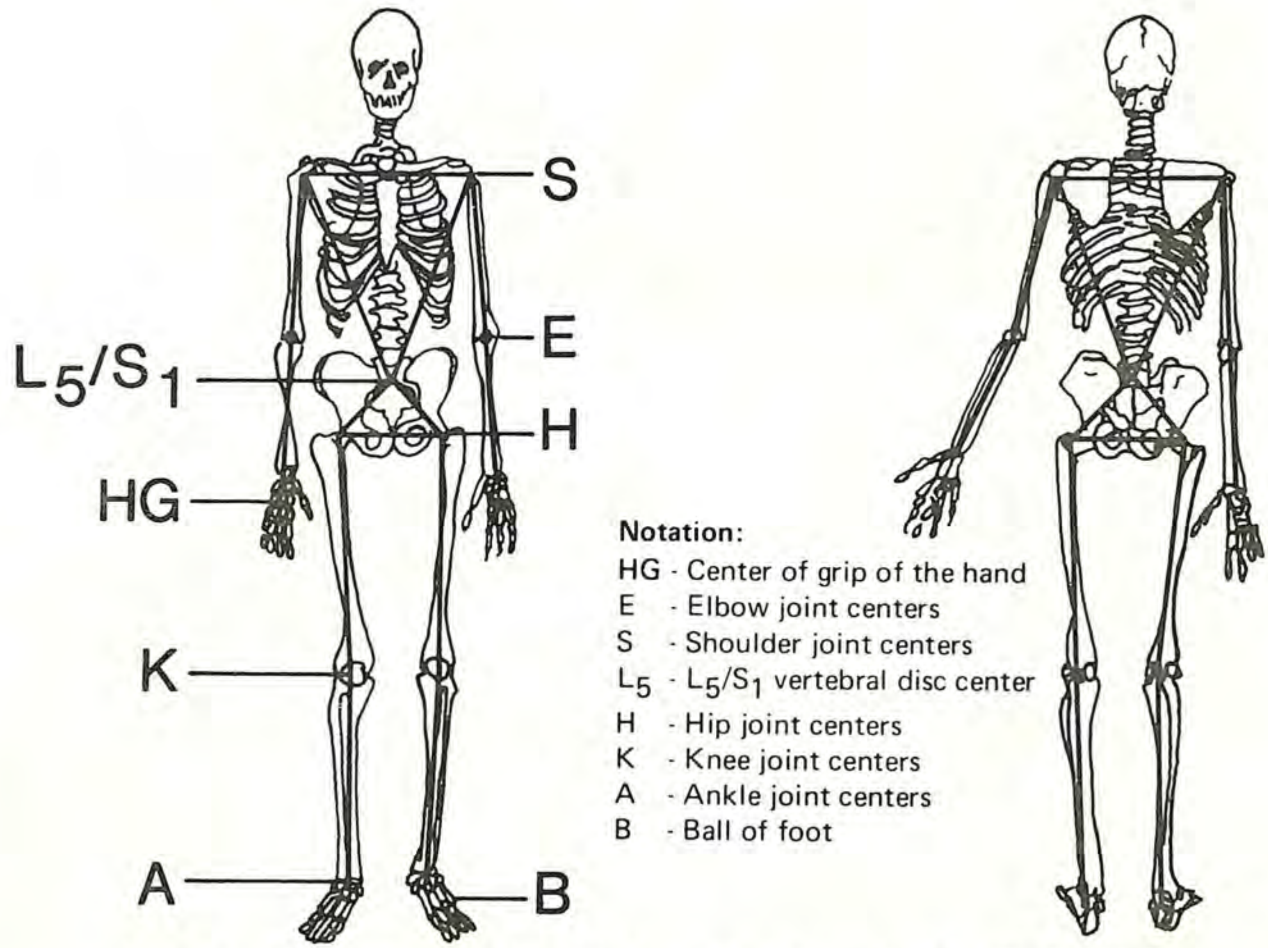

Figure 1. Linkage representation of the human body (from Garg and Chaffin, 1975).

1972; Williams and Stutzman, 1959). Thus, by using a polynomial regression analysis of 18 (10 males and 8 females) people's elbow flexion strength at different positions, the group's average value can be expressed as follows:

$$VT(\text{in.-lb}) = 336.29 + 2.088 \times \alpha - 0.015 \times \alpha^2 - 3.364 \times \beta + 0.019 \times \beta^2 \quad (1)$$

where:

- VT = mean maximum voluntary elbow flexion reactive torque (in.-lb)
- α = elbow included angle (degrees)
- β = shoulder vertical abduction angle (degrees).

This equation has adjacent angles α, β due to the flexor muscles spanning two joints. This is often the case.

To account for individual characteristics, the maximum voluntary torque predicted in Equation (1) is multiplied by a factor called the "subject strength coefficient" designated C_i and by "left-right adjustment" designated C. An individual's elbow flexion strength is then represented as:

$$VT_i = C_i \times C(336.29 + 2.088 \times \alpha - 0.015 \times \alpha^2 - 3.364 \times \beta + 0.019 \times \beta^2) \quad (2)$$

where:

- C_i = subject strength coefficient
- C = a parameter to account for the difference in right and left elbow strengths. For example, on an average for a right handed person, C_i equals 1.00 for right elbow and 0.93 for left elbow, as stated by Schanne (1972). "Left-right adjustment" is only for the arm strengths. It is assumed to be the same for all other strengths.

The subject strength coefficient (C_i) is defined and calculated as follows:

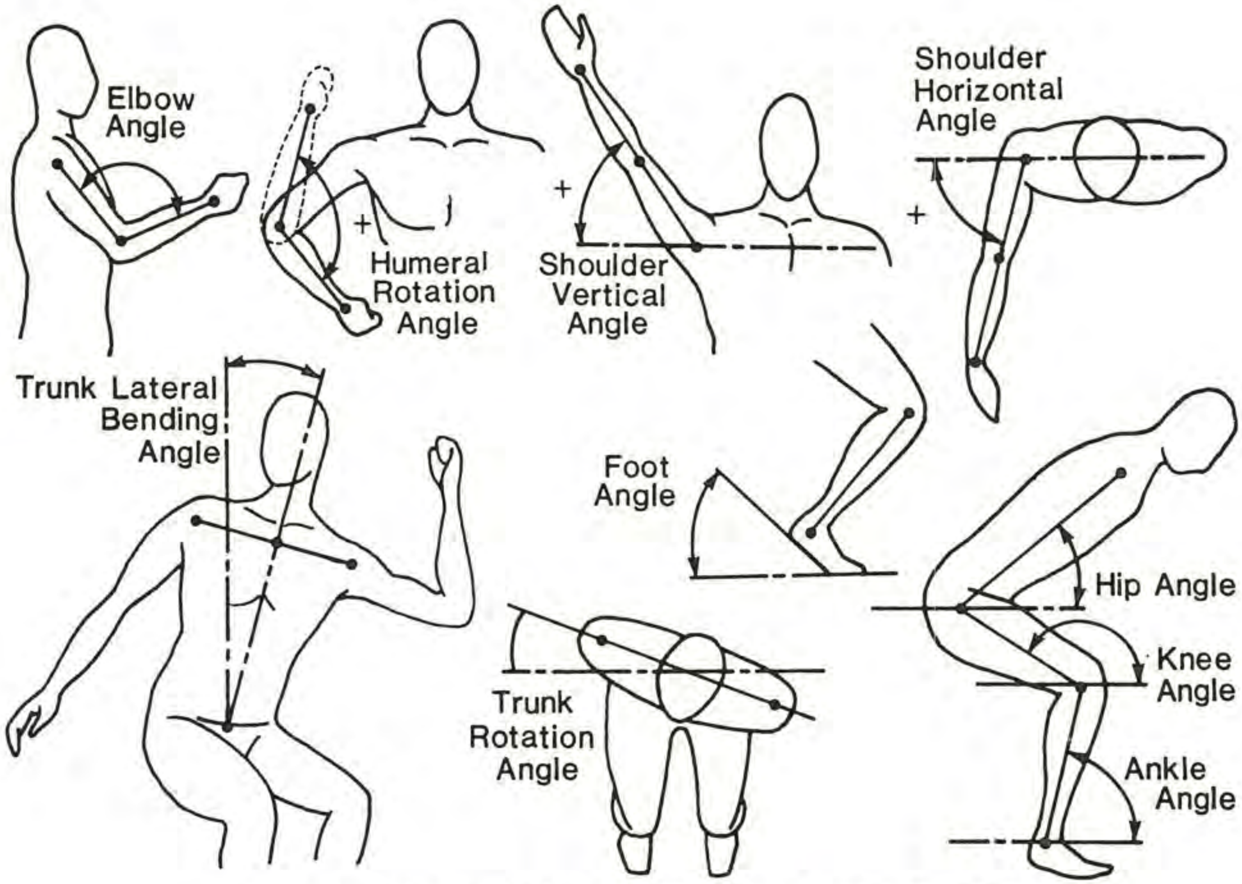

Figure 2. Reference body angles (from Garg and Chaffin, 1975).

$$C_i = \frac{\left[\begin{array}{l}\text{Maximum measured strength (reactive torque) of}\\ \text{a given muscle group for a selected body position}\\ \text{(body angles) of } i^{th} \text{ subject}\end{array}\right]}{\left[\begin{array}{l}\text{Predicted mean strength (Equation 1) of the same}\\ \text{muscle group for the same body position over all}\\ \text{subjects considered in population.}\end{array}\right]}$$

For example, let the selected position for determining C_i for elbow flexion be $\alpha = 90°$ and $\beta = 0°$. Let the measured elbow flexion reactive torque be equal to 623 in.-lb. From Equation (1), VT = 403 in.-lb. Therefore, C_i for elbow flexion equals 623/403, equals 1.4963.

Knowing C_i, the subject's elbow flexion voluntary torque can be predicted for all arm positions by using Equation (2). For example, if the new position of interest is $\alpha = 135°$ and $\beta = 45°$, from Equation (2):

$$VT = 1.4963 \times C \times (336.29 + 2.088 \times 135 - 0.015 \times (135)^2 - 3.364 \times 45 + .019 \times 45^2)$$

Taking C = 1 (right-handed subject using right elbow) VT = 346.977 in.-lb.

The projection technique is represented in Figure 3.

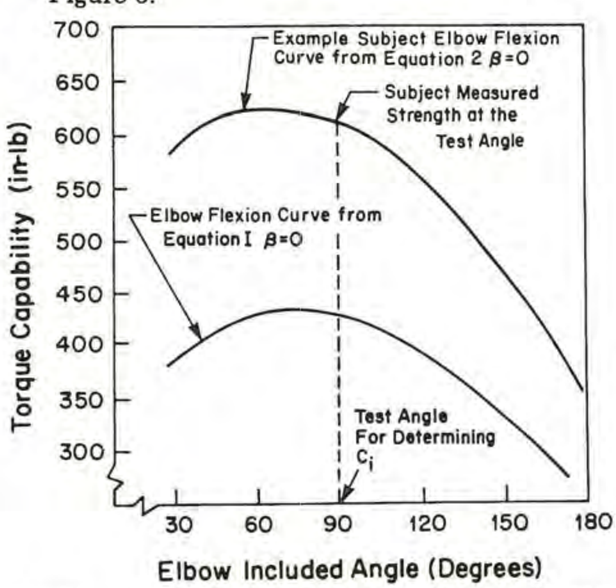

Figure 3. Example of subject elbow flexion capability for various elbow angles (from Schanne, 1972).

Fourteen different subject strength coefficients are required in the present model to represent the different muscle groups of the arms and torso. Five additional strength coefficients are required for the hips, knees, and ankles. Although voluntary torque equations involve more than one articulation angle, it is assumed that the strength of a particular muscle group is not dependent on the level of loading on adjacent articulations. There is some unpublished evidence that this is true for leg strengths. When the model is used for a general population study, these subject strength coefficients are normalized to represent 5, 50, and 95 percentile populations and are available both for male and female populations.

As mentioned earlier, motivation of the subjects should be considered when interpreting the output of the model. It has been proposed in earlier work that a person instinctively limits maximum voluntary efforts when he/she "senses" possible damage to the body (Chaffin, 1974). This limit is hypothesized to be approximately 80% of the true physiological limit, so that the model predictions for muscle strengths are considered to have a margin of safety. But there is still a question regarding maximal allowable compressive limit for the spine. For a detailed explanation see Chaffin (1974).

Following the above procedure establishes the various muscle group strengths for different body postures. These strengths or voluntary torques are then systematically compared with the resultant torques at the joints resulting from gravity acting on both an object being handled and on the body masses. In doing this, if a specific posture has not been inputted, then the model will iterate through various angles at the joints, keeping the hands and feet in the same relative position. With each iteration of a posture, all the voluntary torques of the joint are checked to determine the maximum load that can be applied to the hands to cause a resultant torque to equal one of them. This hand load is then the maximum predicted strength of the body in that posture. All postures that allow the person to reach the designated hand position without exceeding a joint range of motion or without causing the person to lose balance are analyzed in a similar way. The largest predicted hand load for the feasible postures is declared the maximum capability of the person designated to perform the task. The gross macro logic of the model is depicted in Figure 4. A spinal compression analysis is also performed as described by Chaffin (1975a) for reference with population norms of others.

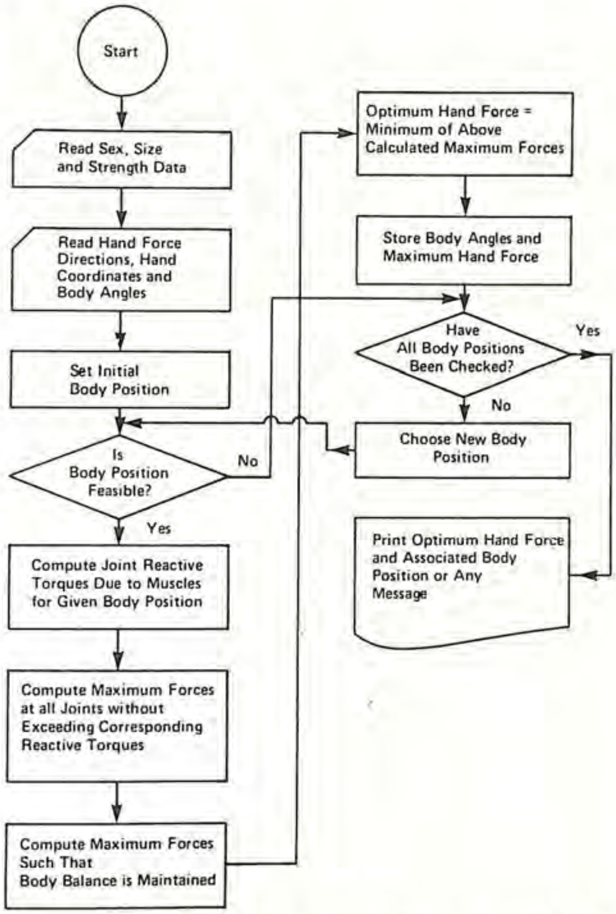

Figure 4. Macro logic flow diagram (from Garg and Chaffin, 1975).

STRENGTH MODEL USAGE AND VALIDATIONS

The usual validation for these types of strength models has been to have a group of people of known anthropometry and strength characteristics perform isometric lifting, pushing, and pulling tasks in different postures. Chaffin and Baker (1970) did this on the simpler sagittal plane model with the results that the model predicted the lifting capabilities of the subjects with a simple correlation coefficient of $r = 0.83$. Schanne (1972) also validated his seated operator strength model and concluded that, in general, the correlation coefficient was about 0.90 with a variety of pushing, pulling and lifting activities.

One of the limitations of these two validations is that they were on small numbers of people (about 20 each). Garg and Chaffin (1975) expanded the validation population by using data gathered previously by Thordsen et al. (1972). This provided a much larger data base (i.e., 71 subjects performing pushes, pulls, and lifts while in 38 different postures). One limitation, however, is that specific strength data on the subjects were not available; thus, strengths were assumed based on body weights (a correlation which is only about 0.40). In general, across all positions and actions, the correlation was generally about 0.70. It was also determined in this analysis that some force-producing postures were better predicted than others, thus indicating the need for more specific developmental activities.

The models have been used over the years for both research and task-design purposes. The original sponsor of the work, Western Electric Co., Inc., has used the output predictions of the sagittal plane model to assist in determining the approximate dimensions of a workplace where objects would be handled (Chaffin, 1972b). The NASA Manned Spacecraft Center used both the two- and three-dimensional strength models for determining what force exertions could be expected of the astronauts in a variety of tasks (Chaffin, 1972a). More recently, the Product Safety Commission used the model to extrapolate and interpolate children's strength data for applications in toy and appliance designs (Owings et al., 1975).

As a research tool, the model outputs have been used to depict what various people could do in different jobs. This served as the basis for a Lifting Strength Rating System for job analysis, which has been found to indicate that high-strength-requiring jobs result in increased incidence of low back pain (Chaffin and Park, 1973). The model has also been used by one company to evaluate the physical demands of over 500 jobs to determine which tasks were potentially overstressing to the musculoskeletal system and what percentage of female and male workers could probably perform each job in the plant.

Currently, a major thrust is to determine how simple, static, muscle-strength tests of employees can be effectively used to place people on jobs that have been rated to require significant biomechanical effort.

SUMMARY

The development of biomechanical strength models has steadily progressed over the last 10 years. Presently, some working models have evolved that assist in answering specific research and practical problems. Still, much needs to be done in this field.

Research to better depict the postures chosen by people when handling materials would be useful in specifying more realistic postures. Certainly those postures where the model predictions do not agree with the strengths demonstrated by various people need to be carefully evaluated and the basis researched.

The dynamic models proposed by Pearson et al. (1963) and Fisher (1967) need to be expanded to include data regarding muscle coordination in common industrial activities. Development of a closer relationship between static and dynamic muscle strengths in industrial tasks is needed.

Also, the limitations of the spinal column's load carrying capability needs to be determined. Limits have been suggested from both cadaver studies and epidemiology studies. If utilized in the models, they would indicate the major limits of what people could handle safely.

In summary, biomechanical strength models allow a logical interpretation and use of specific strength values. The precision and generalization of results, however, must be carefully examined and developed.

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DYNAMIC BIOMECHANICAL MODEL FOR SAGITTAL PLANE LIFTING ACTIVITIES

M. M. Ayoub and M. M. El-Bassoussi

INTRODUCTION

According to Muller (1962), "the object of determining physical work capacity in the industrial sphere is to fit the job to the worker so that he can work without fatigue or harm to his health." This is the essence of current ergonomic philosophy. In repetitive physical tasks, the magnitude of physical work capacity (PWC) in relation to the physiological demands of the task is of primary concern. In fact, PWC determines whether an individual can perform a repetitive physical task for long periods. In heavy physical tasks performed occasionally, however, the PWC is not of prime importance. Instead, the investigator should be more concerned with other measures of work capacity such as the size, strength, and the condition of the musculoskeletal system in general in relation to the forces and torques imposed on the body while performing these tasks (Knipfer, 1974; Chaffin and Baker, 1970). Manual materials handling, depending on the weight handled, frequency, method, and posture during lifting, can fit either of the task categories discussed above (Knipfer, 1974).

The interest in studying and analyzing manual materials handling and lifting in particular stems from the increase in reported injuries resulting from these tasks. Brown (1970) reported that the handling of materials has been a major source of injury to workmen in industry. Jones (1971) reported that more than 20% of the compensation dollar in Ontario is often spent on lower back pain. Troup (1965) reported that a relatively large portion of industrial injuries (as great as 12%) are back injuries resulting from lifting tasks. The incidence of low back injuries is highest among operators in the heavy industries (Magora and Taustein, 1969).

Studies by Armstrong (1965), Morris et al. (1961), Munchinger (1962), and Roaf (1960) indicated that injuries to the spine due to lifting seem to be concentrated on the lower vertebral bodies and intervertebral discs. Excessive compressive forces on the spine will cause fractures of the vertebral bodies (Nachemson, 1962; Perey, 1957). Hyperflexion or hyperextension may also cause injuries to vertebral bodies (Roaf, 1960). The types of disc injuries are degeneration, protrusion, and herniation. Hirch (1951) believes that disc degeneration is correlated with age; Perey (1957) and Gordon (1961) believe that disc degeneration is also dependent on the magnitude of day-to-day forces on the discs.

To provide objective criteria for assessing the lifting strain, all relevant kinematic and kinetic parameters for the body and its segments, and, therefore, for the task itself, must be taken into consideration to better evaluate the stress imposed on the musculoskeletal system, particularly the spine. This paper describes the development and application of a dynamic biomechanical model of sagittal lifting activities for simulation of lifting actions and to determine the resulting lifting strain.

BIOMECHANICS AND LIFTING TASKS

The traditional approach for evaluating biomechanical forces, torques, and work has been to isolate those body segments involved, to estimate their mass and location of mass center, and to make the necessary assumptions concerning the body articulations that will allow analysis according to the laws of mechanics. For static analysis, one needs only to measure the body orientation and the external forces acting upon it. For dynamic analysis, however, the inertial characteristics of the body in motion create forces that are an integral part of the total kinematic system. These forces can be ascertained only by studying the body segment displacement with respect to time.

It has been 87 years since Braune and Fisher (1889) published their data regarding the mass distribution for the various body segments. Since then, fundamental extensions by Dempster (1955), Drillis and Contini (1966), and Contini (1972) have resulted in better estimates of the location of the mass centers of gravity, the link lengths, and the magnitudes of the moments of inertia of the various body segments.

A biomechanical model primarily estimates the forces and torques at various articulations of the body during voluntary actions (e.g., lifting, running, or throwing). An early example of this type is a two-link model of the arm developed by Pearson and McGinley (1961). Their intent was to compute the forces and torques at the elbow and shoulder during a sagittal planar motion of the arm-forearm-hand aggregate. Stroboscopic photographs of the various arm motions of interest were taken to determine the instantaneous positions, velocities, and accelerations of the arm segments. These "activity" data, along with the anthropometric dimensions of each segment's length and weight, provided enough input information to compute the stress levels at the elbow and shoulder. A means was thus provided to achieve a better understanding of both the complex muscle actions required for control of the arm and the resulting strain at the articulations.

An extension of the Pearson Arm Model was developed by Plagenhoef (1966). Again, photographic data were used to describe the body configurations during the relevant task. These spatial data, combined with additional anthropometric dimensions regarding the length of the arm, trunk, and leg segments and the total weight of the subject, provided adequate information to compute the forces and torques at the elbow, shoulder, hip, and knee during various physical activities performed in the sagittal plane.

The Static Sagittal Plane Lifting (SSPL) model was introduced by Chaffin (1969). As the name infers, this particular model has been developed to evaluate various static situations, such as when one is holding a weight or pushing or pulling on a nonmoving container. In addition to these applications, the model may be used to analyze slow moves by formulating the input data to describe a sequence of static positions with very small changes in each successive position. In making this type of pseudodynamic analysis, it must also be assumed that the effects of acceleration and momentum are negligible, which is not intrinsic. A later extension of the model using estimated values of accelerations was reported by Park and Chaffin (1974).

Essentially, two differences occur between the static and dynamic activities. First, in the dynamic case, the external forces exerted on the segments do not necessarily act in the same direction. This requires vector addition of the forces, which is not required in the static lifting case where all forces act in the parallel direction of gravity. A second, additional requirement for transforming the static model into a dynamic one is to include an inertial torque at each segment's center of gravity. This characterizes the force created by rational acceleration of the segments about their gravity centers.

Several assumptions must be made to apply mechanics to the body. These assumptions are:

1. The body is made of rigid links joined at body articulation points.

2. The joints are pin centered; therefore, the instantaneous center of rotation of each joint does not shift in space as the joint is rotated.

3. The center of mass of each segment (link) maintains its location with respect to the proximal and distal joints when the distal segment moves.

THE DYNAMIC MODEL

Modeling of Angular Displacement, Velocity, and Accelerations

The Slote and Stone (1963) space-time relationship was used to determine and model the angular displacement for each segment. The relationship can be expressed by the following equation:

$$D_i = \frac{D_{max}}{2\pi}\left[\frac{2\pi t_i}{T} - \sin\frac{2\pi t_i}{T}\right] \qquad (1)$$

where

D_i	=	angular displacement in radians
D_{max}	=	maximum angular displacement, radians
T	=	total articulation displacement time, seconds
t_i	=	time interval during the movement of the articulation

Based on the above relationship, the angular velocity (V_i) and the angular acceleration (A_i) can be expressed as:

$$V_i = \frac{dD_i}{dt} = \frac{D_{max}}{T}\left[\frac{1\text{-}\cos^2 2\pi t_i}{T}\right] \qquad (2)$$

and

$$A_i = \frac{d^2D_i}{dt^2} = \frac{2\pi D_{max}}{T^2}\sin\frac{2\pi t_i}{T} \qquad (3)$$

Equations 1, 2, and 3 were used to calculate the kinematics of motion for each of the segments in this model. These are the lower leg, the upper leg, the trunk, the upper arm, the forearm, and three segments in the lumbar spine. The equations are functions of the maximum displacement (D_{max}) and the total displacement time (T). Therefore, these two parameters were measured experimentally so that the acceleration profiles could be calculated. Figure 1 shows the various acceleration vectors at the center of mass for each segment due to rotation about the joints.

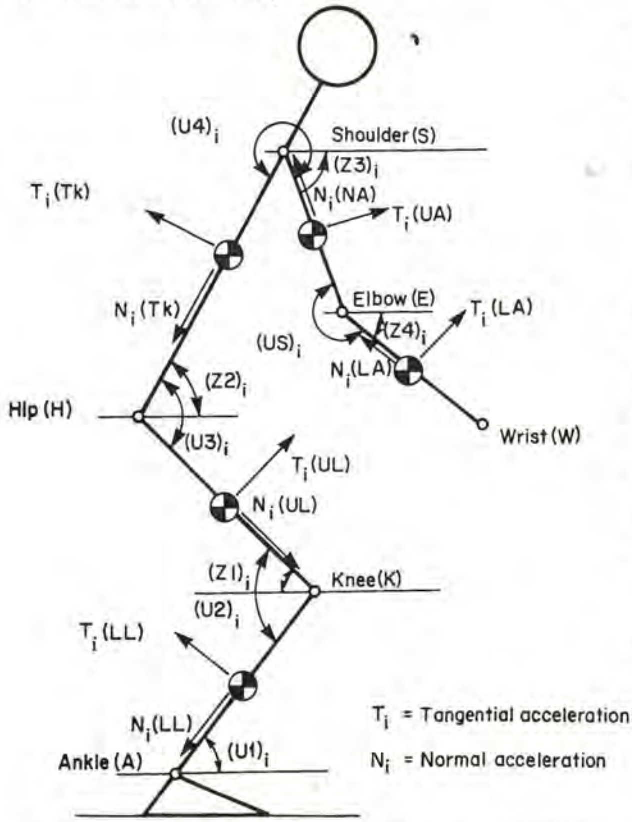

Figure 1. The angular acceleration components at the center of gravity of each body segment.

Computation of Linear Accelerations for the Segments

Starting from the ankle joint, the tangential and normal accelerations due to rotation of the lower leg around the ankle joint were computed from the angular accelerations determined from Equation 3 above.

$$\text{Tangential acceleration} = (a - CG_{11})\, A_i$$

$$\text{Normal acceleration} = (a - CG_{11})\, V_i^2$$

where

$(a - CG_{11})$ = the distance between the center of ankle joint to the center of mass of lower leg

A_i = angular acceleration due to rotation of knee about the ankle joint

V_i = angular velocity due to rotation of knee about the ankle joint

Similar calculations were performed for the remaining segments. The tangential and normal acceleration components at each center of mass were resolved to form horizontal (X component) and vertical (Y component) components. From these linear acceleration components and by taking into account their additive effects, the resultant linear acceleration at the center of each segment was computed.

Computation of Reactive Forces and Torques at Body Articulations

The masses of the body segments and the mass of the load handled produce forces and torques on the body segments. Also, the accelerations of the weight handled and the body segments produce forces and torques on the body segments. By using the same approach of Slote and Stone (1963), the reactive forces and torques can be calculated. In Figure 2, the reactive forces and reactive torques acting on the arm are illustrated. The same procedure for determining these forces and torques was used in determining the reactive forces and torques on the remaining segments.

The following equations give a sample of the calculations needed to determine the reactive forces and torques acting at the wrist and the center of mass of the hand:

$$F_i\,(HA)/X = -\,[m(HA) + m(L)] \cdot XX_i\,(HA) \qquad (4)$$

$$F_i\,(HA)/Y = -\,[m(HA) + m(L)] \cdot YY_i\,(HA) \qquad (5)$$

$$T_i\,(HA) = -\,I_{CG(HA)} \cdot (\ddot{U}_5)_i \qquad (6)$$

$$R_i\,(W)/X = -\,F_i\,(HA)/X \qquad (7)$$

$$R_i\,(W)/Y = -\,[F_i\,(HA)/Y + W(HA) + L] \qquad (8)$$

$$M_i\,(W) = -\,T_i(HA) + F_i(HA)/X \cdot r_6 \cdot \sin(Z_4)_i - [F_i(HA)/Y + W(HA) + L] \cdot r_6 \cdot \cos(Z_4)_i \qquad (9)$$

where

$F_i\,(HA)/X$ = horizontal inertial force in kg acting at the center of gravity (CG) of hand

$F_i\,(HA)/Y$ = vertical inertial force in kg acting at the CG of hand

m (HA) = mass of the hand in kg

m (L) = mass of the load in kg

XX_i (HA), YY_i (HA) = horizontal and vertical components, respectively, for linear acceleration in cm/sec^2 at time in-

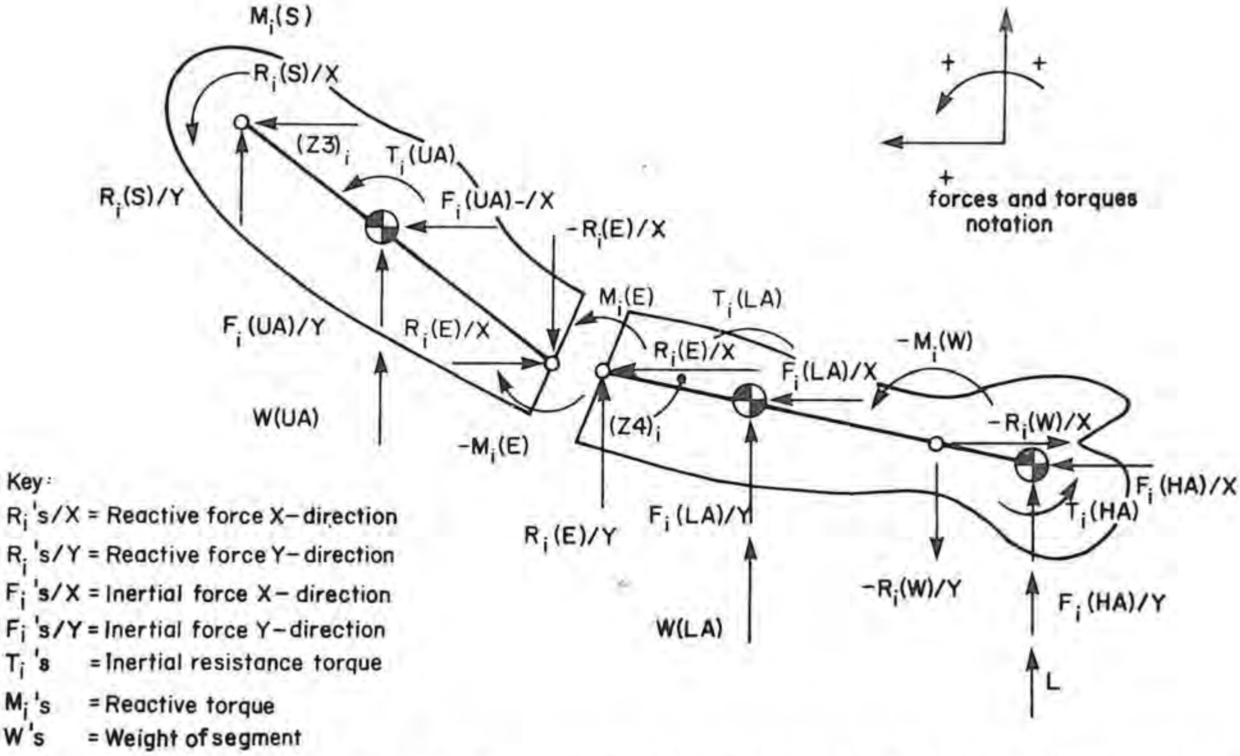

Figure 2. Free body diagram for the arm showing the forces and torques during the dynamic activity of lifting.

terval i acting at the center of gravity of the hand

T_i (HA) = inertial resistance torque in kg - cm acting at the CG of the hand

$I_{CG(HA)}$ = moment of inertia of the hand (kg - cm^2)

$(\dot{U}_5)_i$ = angular acceleration in radians/sec^2 at a time interval i due to rotation about the elbow joint

R_i (W)/X = horizontal reactive force in kg acting at the wrist joint

R_i (W)/Y = vertical reactive force in kg acting at the wrist joint

W (H) = weight of the hand in kg

L = weight of the load in kg

M_i (W) = reactive torque in kg - cm acting at the wrist joint

r_6 = distance between CG of hand and center of wrist joint (cm)

$(Z_4)_i$ = angle between the line connecting center of wrist joint and CG of hand and the horizontal line passing through the wrist joint center (radians)

Calculations of Compressive and Shear Forces on the Lumbar Spine

Since the main areas of concern in the spine are the L-4/L-5 and L-5/S-1 intervertebral discs and the surrounding vertebral bodies, it will be assumed that the centers of the two discs are the centers of the articulations. This is the same assumption made by Fisher (1967). The trunk was divided into three links:

a - hip joint to center of L-5/S-1 disc

b - center of L-5/S-1 disc to center of L-4/L-5 disc

c - center of L-4/L-5 disc to shoulder joint

The average spinal dimensions as determined by Fich (1904) and used by Fisher (1967) were utilized in the model. Fisher's estimates of the masses of these links and their center of masses were also used. Mitchell (1934) measured spinal angles in the erect position. This information, coupled with curvature changes during sagittal rotation of the hip based on data by Dempster (1955), Park and Chaffin (1974), Davis et al. (1965), Albrock and Uganda (1957), Lindahl (1966), and Rolander (1966), was used to define the orientation of L-4, L-5, and S-1 in the sagittal plane. This orientation made it possible to calculate compressive and shear forces on the spine during the lifting action.

The contribution of intra-abdominal pressure in relieving compression of the lumbar spine is well documented (Morris et al., 1961; Troup, 1965; and Chaffin, 1969). Therefore, in the calculations of compressive and shear forces, forces resulting from abdominal pressure were considered. These forces are dependent on the effective abdominal areas and the degree of hip flexion (Morris et al., 1961; Chaffin, 1969). By using the data on dimensions of the spinal angles, the reactive forces and torques on these links were determined during lifting actions. Figure 3 presents the free body diagram for the middle link in the spine (L-4/L-5 to L-5/S-1) showing the reactive forces and torques on this link.

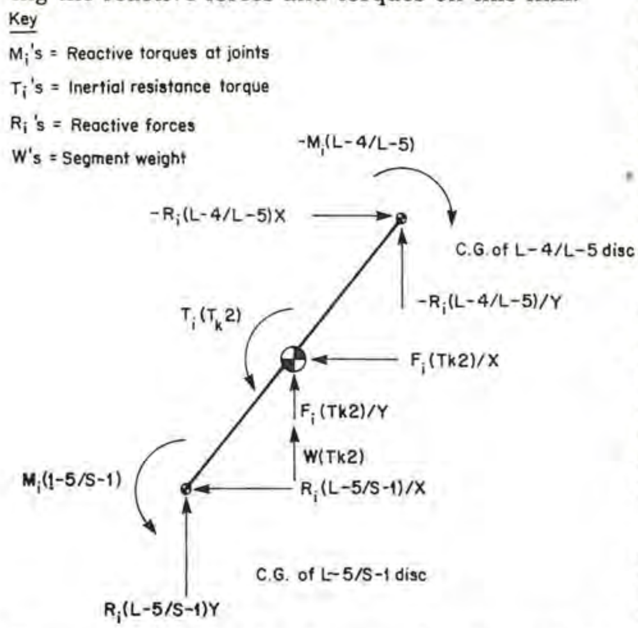

Figure 3. Free body diagram for the middle trunk link showing forces and torques during dynamic lifting.

In addition to the normal forces on the spinal links as a result of body weight and external forces, the additional forces resulting from the tension in the erector spinae muscle, which counteract the torque around the discs, are included. This is accomplished by assuming a line of action parallel to the vertebral bodies, 50 mm posterior to the center of the discs (Bartelink, 1957; Pearson and McGinley, 1961; Perey, 1957; Thieme, 1950).

MODEL INPUT-OUTPUT DATA

The dynamic biomechanical model requires the following input data:

- body segment parameter data,
- external weight carried,
- initial and final configurations of the body links, and
- total movement time for each link with its relation to other links.

The model gives the following output data:

- displacement-time data for each articulation,
- the profiles of velocity and acceleration for each link,
- reactive forces and torques at each articulation, and
- compressive and shear forces on L-4, L-5, and S-1 and their intervertebral discs.

MODEL APPLICATION

The model was used to determine the strain on the musculoskeletal system during the lifting action using leg lifts and back lifts for five subjects. These two methods of lifts were compared while lifting loads of 10, 20, and 30 lb (4.5, 9.1, and 13.6 kg) using three box sizes of 12 × 12 × 6 in., 18 × 12 × 6 in., and 24 × 12 × 6 in. (respectively, 305, 455, 610 × 305 × 150 mm). The box sizes had the effect of displacing the center of gravity of the load away from the spine.

The comparison is made in terms of the hip torque, compressive and shear forces on L-4/L-5 and L-5/S-1, and the postures during the action of lifting where maximum compressive and shear forces occur. The model also provides a simulation of the lifting action for both methods of lift showing the path taken for each articulation during the lifting actions.

The maximum compressive forces acting on the upper surface of L-5 are shown in Figure 4. The biomechanical equivalent (Tichauer, 1971) used for the abscissa as an index of lifting stress com-

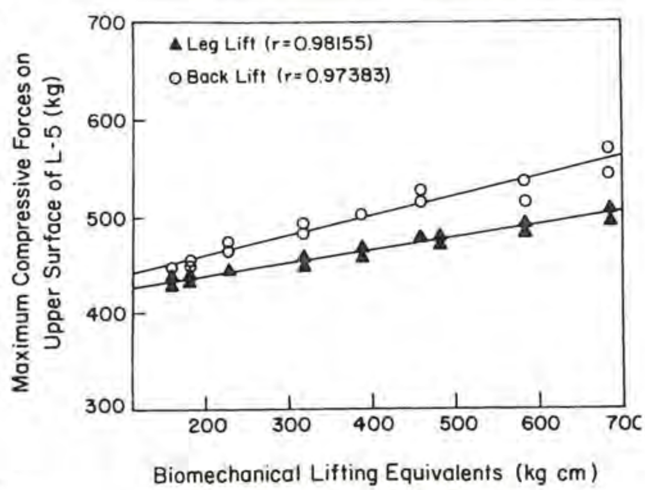

Figure 4. Relationship between the biomechanical lifting equivalents and the maximum compressive forces on upper surface of L-5.

bines the weight of the load and the distance of its center of gravity from the spine. This biomechanical equivalent is calculated as follows in Imperial units:

$$\text{Biomechanical equivalent} = (8 \text{ in.} + L/2)W$$

where

L = length of box handled (in this case, 12, 18, and 24 in.)

W = external weight lifted (10, 20, and 30 lb)

The maximum compressive forces on the upper surface of L-5 for both methods of lift are shown in Figure 4. These data clearly show that maximum compressive forces for back lift are higher than those for leg lift for these conditions of load and speeds of lift. As the lifting task becomes more stressful, as defined by the biomechanical equivalent, the rate of change in the stress on L-5 increases at a higher rate for the back lift method than for the leg lift method (Figure 4). Similar results are found for compressive forces on L-4 and S-1.

Figure 5 shows the most stressful posture during the lifting action for both leg and back lifting. It should be noted that in either method of lift, the most stressful posture occurs quite early after the lifting action has started. The biomechanical model also provides data on the compressive forces and shear forces as the posture of the operator progresses through the lifting action. Figure 6 shows the changes in the compressive and shear forces on L-4 as the operator's posture changes during the lifting action for both back and leg lifting.

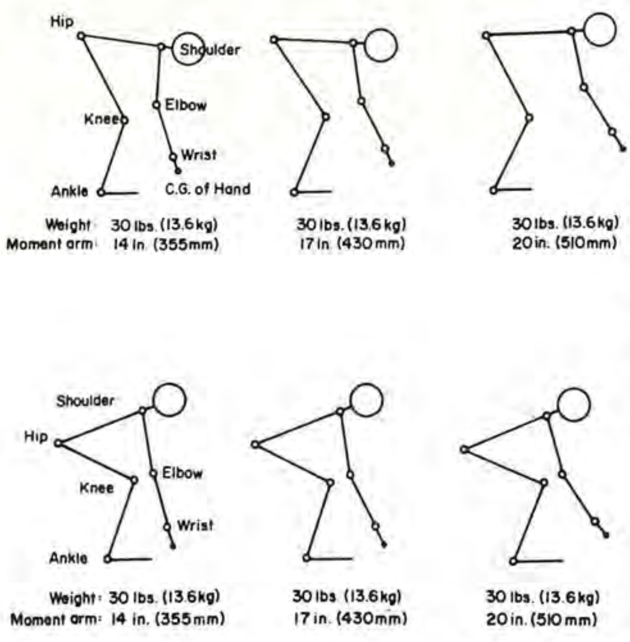

Figure 5. Critical positions for back lift (top) and leg lift (bottom) using the same weight of lift and different moment arms.

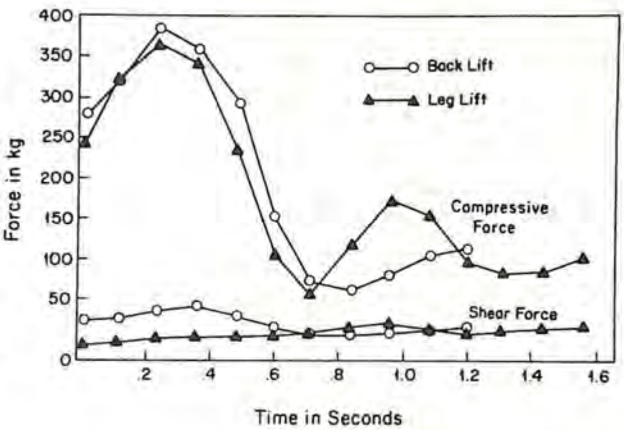

Figure 6. Changes in compressive and shear forces on L-4 for back and leg lifting during the lifting action (Subject No. 4; 10 pounds; and 20 inch box length).

This shows these forces increasing rapidly, reaching a peak quite early, and gradually decreasing in value towards the end of the lift. The model also serves as a means of simulating the lifting action; the posture taken by the operator as a function of time for both methods of lift is shown. In Figure 7, these postures for back and leg lifting are illustrated. The results also show the linear changes in these stresses and the increased difficulty of the task when the box length is increased.

MODEL LIMITATIONS

In addition to the limitations due to the assumptions that must be made to apply Newtonian mechanics, the model is only two-dimensional and, therefore, is somewhat limited in scope. Torsional moments of the spine not considered in this model are of prime importance in making a comprehensive assessment of lifting stresses. Biomechanical models for lifting have not, until now, considered the effects of repeated lifting on the movement kinematics and, therefore, have not considered the changes in both the coordination of the lifting action as well as the resulting changes in inertial

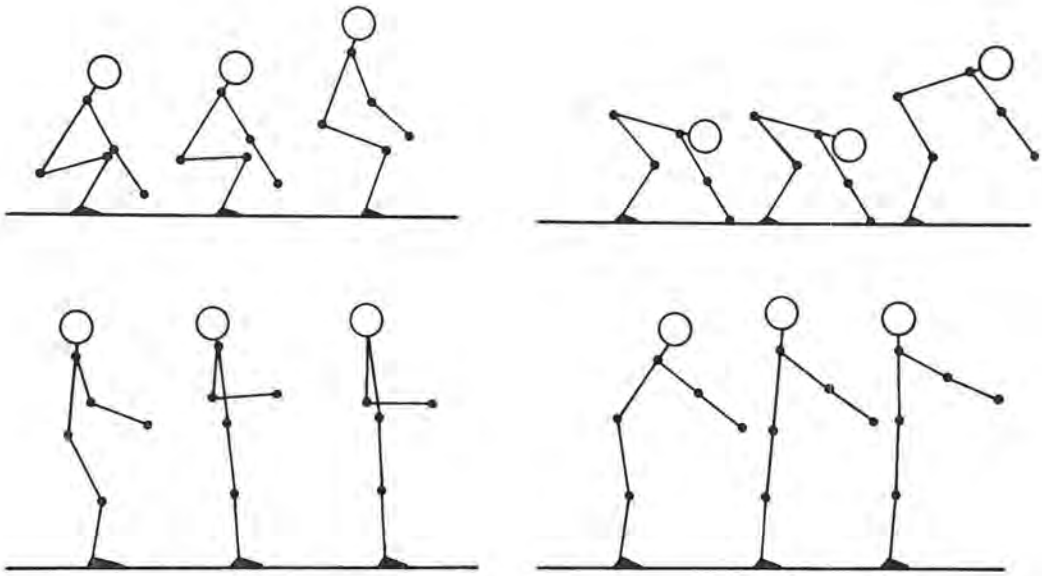

Figure 7. Postures taken through the lifting action.

forces and torques. These are some of the limitations currently under further study; the hope is that solutions can be incorporated in the model to reduce or eliminate these limitations.

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A NONLINEAR PROGRAMMING MODEL FOR THE DESIGN AND EVALUATION OF LIFTING TASKS

M. B. Muth, M. A. Ayoub, and W. A. Gruver

INTRODUCTION

Most analyses of lifting problems concern themselves with the experimental approach, i.e., subjects would perform a lifting task under a variety of conditions, and a number of physiological indices would be monitored. A statistical analysis would then be used to determine the effects of various human and other variables upon the physiological cost of the task. Following this, a set of predictive models would be developed. These models usually express the physiological cost in terms of some basic task, human, and work place variables (e.g., Frederick, 1959; Aberg, 1968; Snook and Irvine, 1967; Ayoub, 1971; Drury and Pfeil, 1975; Roozbazar, 1974).

A second approach for analyzing lifting tasks that is frequently used is biomechanical in nature. This approach utilizes basic mechanics with experimental data for the purpose of making predictions concerning the task and its physiological demands (e.g., Martin and Chaffin, 1972; Tichauer, 1971). The biomechanical approach differs from its experimental counterpart in that it attempts to predict directly the stress and strain of a given task rather than indirectly through such techniques as regression analyses.

In recent years the use of models that are based on the use of optimization for analyzing lifting and similar problems has proved to be a viable alternative (Ayoub, 1971; Chow and Jacobson, 1971; Ghosh and Boykin, 1975; Seirig, 1975; Ayoub and Elshafei, 1974). The fundamental assumption motivating all these models is that an individual will optimize his performance consistent with task and work place constraints, i.e., the principles of optimality in biomechanics will be followed. The use of optimization models in dealing with lifting problems (and, for that matter, manual materials handling in general) provides more than an alternative method for the evaluation and assessment of lifting tasks. Indeed, through modeling, a task can be designed and evaluated without the need for comprehensive experimentation and elaborate data collection and analyses.

This paper presents an optimal programming model to be used for the design and evaluation of lifting tasks. The input data for the model, which are basic and can be obtained without extensive experimentation, include (1) anthropometric characteristics of the individual who would perform the task, (2) characteristics of the object to be lifted (size, weight, etc.), (3) initial and final positions of the object, and (4) the task performance time. In the following sections, the model formulation, model solution, and the application of the model to analyze some lifting tasks will be presented.

MODEL FORMULATION

Assumptions

The human body when viewed in the sagittal plane can be considered as five rigid links (Figure 1). These links are of the same length as their corresponding human segments and possess the same mass and moment of inertia as their human counterpart. Thus, any movement or configuration of the body can be described in terms of the angular positions of these five geometrical links. For the purpose of this study, the link from the shoulder to the hip (spinal column) is considered as one rigid link, i.e., spinal flexion is not considered for the model. Some models, however, such as that of Chaffin and Martin (1972) allow for spinal flexion. It is also assumed that the head and neck are part of the back's mass. The hands in this abstraction of the body are assumed to be part of the elbow to wrist structure. Thus, there does not exist a wrist joint; in lifting a load, the hands are assumed to have no relative motion with respect to the forearms. Using these five links as described, it is possible to apply principles of mechanics to describe any motion of the human body while performing lifting tasks.

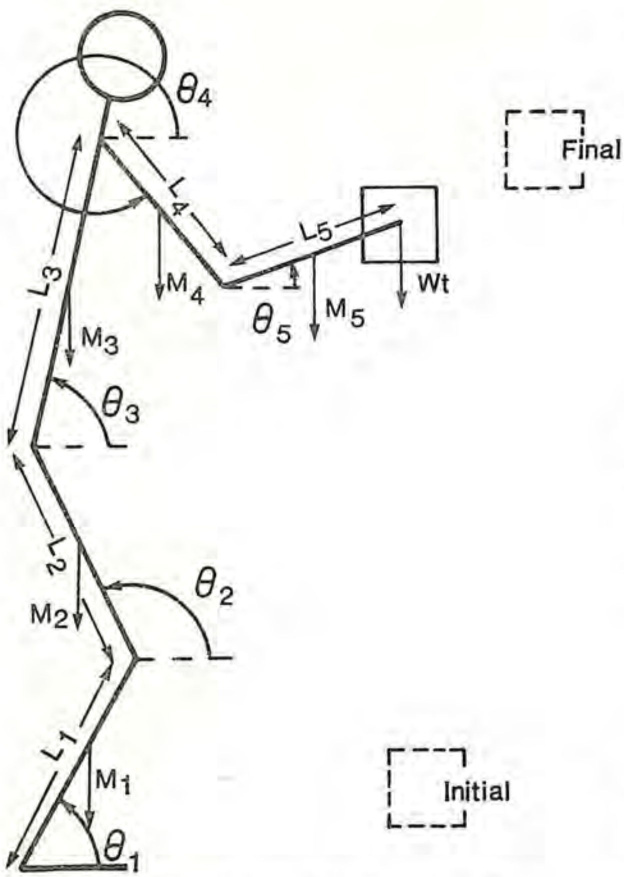

Figure 1. Five-link model of worker lifting.

The class of motions to be considered by the model is somewhat restrictive. It is assumed that the worker does not walk with the load and that he remains stationary and lifts the object between two preselected points in the task space. The object, then, must be within arm's reach at the beginning of the task and at the end of the task. All movement during the lift is symmetrical, i.e., each arm moves in unison with the other arm (as also do the legs). The ankle is considered fixed on the floor, ignoring the joint at the ball of the foot. Finally, the motions considered during the lift are those motions occurring only in the sagittal plane. For example, body rotation from side to side (i.e., motions that occur in two different planes) is not considered as a feasible motion by the model.

Dynamics of Lifting

To describe the motion of the worker performing a lifting task, the methodology of basic mechanics must be applied. A Cartesian coordinate system is assumed, with the origin situated at the ankle joint.

The acceleration for an intermediate link about a point (such as the wrist rotating about the elbow) during any instant t of its motion can be written as:

$$ax(t) = -\dot{\theta}^2(t)\, l \cos\theta(t) - \ddot{\theta}(t)\, l \sin\theta(t)$$
$$ay(t) = -\dot{\theta}^2(t)\, l \sin\theta(t) + \ddot{\theta}(t)\, l \cos\theta(t)$$

where

l = the distance of the object from the center of rotation

$\theta_i(t)$ = the angular displacement of the link
$\dot{\theta}_i(t)$ = angular velocity
$\ddot{\theta}_i(t)$ = angular acceleration.

The equations for the linear accelerations of each joint of the link model are

$$ax_1(t) = 0$$
$$ay_1(t) = 0$$
$$ax_{i+1}(t) = -\, l_i[\dot{\theta}_i^2(t)\cos\theta_i(t) + \ddot{\theta}_i(t)\sin\theta_i(t)] + ax_i(t)$$
$$ay_{i+1}(t) = ay_i(t) + l_i\,[-\,\dot{\theta}_i^2(t)\sin\theta_i(t) + \ddot{\theta}_i(t)\sin\theta_i(t)] \qquad i = 1,\ldots,4$$

The linear accelerations of the center of mass of the *ith* link can also be written as:

$$agx_i(t) = ax_i(t) - r_i[\dot{\theta}_i^2(t)\cos\theta_i(t) + \ddot{\theta}_i(t)\sin\theta_i(t)] \qquad i = 1,\ldots,5 \qquad (1)$$
$$agy_i(t) = ay_i(t) + r_i[-\,\dot{\theta}_i^2(t)\sin\theta_i(t) + \ddot{\theta}_i(t)\sin\theta_i(t)]$$

where r_i is the distance of the center of mass from the proximal point of the *ith* link.

To lift a load, a worker must exert a force upon the object. Consequently, an equal and opposite force will be exerted upon the worker. This force will be transmitted through his joints to the surface upon which he is resting. Assuming the worker is able to lift the load, the laws of equilibrium require that the sum of the forces at each joint be zero. (Figure 2 pictures this equilibrium for forearm-hand link.) Thus, it is possible for the forces at each joint to be determined; these are given for any instant t during the motion as follows:

$$Fx_5(t) = -\, m_5\, agx_5(t)$$
$$Fy_5(t) = W + m_5\, agy_5(t) + gm_5$$
$$Fx_i(t) = Fx_{i+1}(t) - m_i\, agx_i(t) \qquad (2)$$
$$Fy_i(t) = Fy_{i+1}(t) + m_i\, g + m_i\, agy_i(t) \qquad i = 1,\ldots,4$$

where m_i = the mass of the *ith* link, and W = the weight of the object to be lifted.

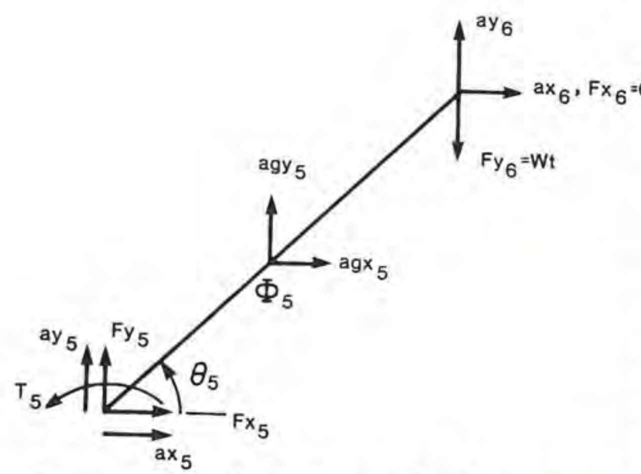

Figure 2. Free body diagram for elbow-to-wrist link.

The torques induced at each joint can be written as:

$$
\begin{aligned}
&T_6(t) = 0 \\
&T_i(t) = T_{i+1}(t) + m_i r_i g\,\theta_i(t) + I_i\,\ddot{\theta}_i(t) \qquad (3)\\
&\qquad + l_i\,(Fy_{i+1}(t)\cos\theta_i(t) \\
&\qquad - Fx_{i+1}(t)\sin\theta_i(t)) \\
&\qquad + m_i r_i\,(agx_i(t)\sin\theta_i(t) \\
&\qquad + agy_i(t)\cos\theta_i(t)) \qquad i = 1,\ldots,5
\end{aligned}
$$

where

$Fx_6(t) = 0$
$Fy_6(t) = W$
$g =$ the acceleration due to gravity
$I_i =$ the moment of inertia for the *ith* link.

Motion Constraints

Certain constraints are imposed upon the lifting motion due to the limitations of the human body. Joints can only bend in certain directions and by a limited amount, thereby constraining the possible positions of the body. This results in constraints on the angles at the joints, $\{\theta_i(t)\}_1^5$:

$$l_{1,i} \leq \theta_i(t) \leq u_{1,i},\ 0 \leq t \leq T \qquad i = 1,\ldots,5 \qquad (4)$$

There also are limits on the speed at which a worker can move. These limits create additional constraints on $\theta_i(t)$ and $\theta_i(t)$:

$$
\begin{aligned}
&\dot{\theta}_i(t) \leq u_{2,i},\ 0 \leq t \leq T \\
&\ddot{\theta}_i(t) \leq u_{3,i},\ 0 \leq t \leq T \qquad i = 1,\ldots,5 \qquad (5)
\end{aligned}
$$

The task itself imposes constraints upon the motion. The object to be lifted has an initial position and a desired final position. The worker is assumed to have an initial position so that his hands reach the object at its initial position, and this initial position of the body must be feasible according to Equation 4. The worker's initial position, then, is given by:

$$\theta_i(0) = A_i \qquad i = 1,\ldots,5 \qquad (6)$$

This initial position for the worker is chosen so that his hands grasp the object, and either his back is straight and his knees are bent, or his back is bent and his knees are straight. Since the object has a desired final condition, the worker must be able to reach it at this point. This results in a constraint on the final position of the worker:

$$\theta_i(T) = B_i \qquad i = 1,\ldots,5 \qquad (7)$$

The final position is chosen so that the worker is standing up with his arms extended and his back bent, if needed, to allow his hands to reach the object. Finally, there often exist obstacles that restrict the worker's movement in performing the task, e.g., a table under which the object is located (Figure 3). An object restricting movement was represented as a circle with a center at (x^*, y^*) and radius R. The

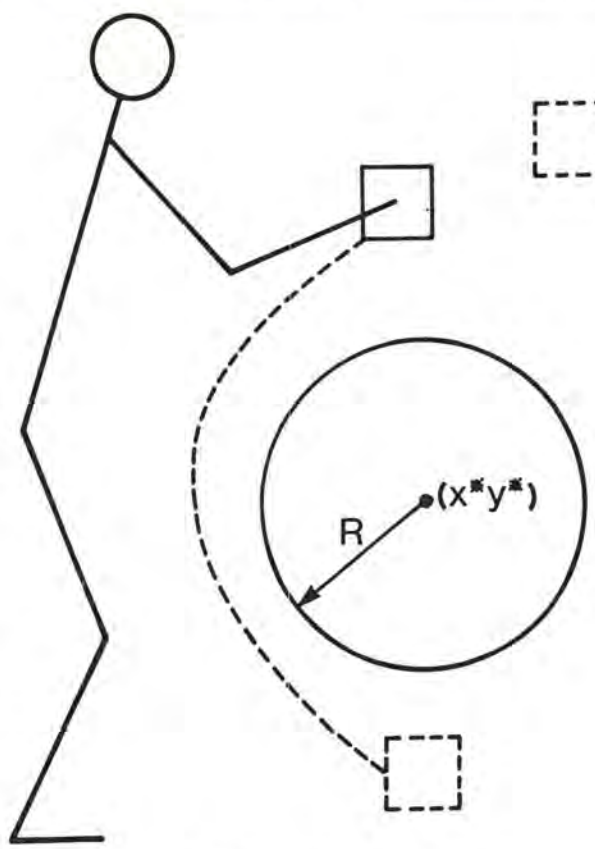

Figure 3. Constrained lifting path.

path of the worker is to be constrained so that the shoulder, elbow, and wrist remain outside the circle. This requirement is represented by the following nonlinear inequality constraints:

$$g_1(x_3(t), y_3(t)) \triangleq (x_3(t) - x^*)^2 + (y_3(t) - y^*)^2 - R^2 \geq 0$$

$$g_2(x_4(t), y_4(t)) \triangleq (x_4(t) - x^*)^2 + (y_4(t) - y^*)^2 - R^2 \geq 0$$

$$g_3(x_5(t), y_5(t)) \triangleq (x_5(t) - x^*)^2 + (y_5(t) - y^*)^2 - R^2 \geq 0$$

where

(x^*, y^*) = the center of the circle

R = the radius of the circle

$(x_3(t), y_3(t))$ = the location of the shoulder

$(x_4(t), y_4(t))$ = the location of the elbow

$(x_5(t), y_5(t))$ = the location of the wrist.

The location of these joints can be written equivalently in terms of the angular positions as:

$$x_i(t) = \sum_{j=1}^{i-1} l_j \cos\theta_j(t) \qquad i = 1,...,5$$

$$y_i(t) = \sum_{j=1}^{i-1} l_j \sin\theta_j(t) \qquad i = 1,...,5$$

The obstacle constraints can therefore be written:

$$g_1(\theta(t)) \triangleq \left(\sum_{i=1}^{2} l_i \cos\theta_i(t) - x^*\right)^2 + \left(\sum_{i=1}^{2} l_i \sin\theta_i(t) - y^*\right)^2 - R^2 \geq 0$$

$$g_2(\theta(t)) \triangleq \left(\sum_{i=1}^{3} l_i \cos\theta_i(t) - x^*\right)^2 + \left(\sum_{i=1}^{3} l_i \sin\theta_i(t) - y^*\right)^2 - R^2 \geq 0$$

$$g_3(\theta(t)) \triangleq \left(\sum_{i=1}^{4} l_i \cos\theta_i(t) - x^*\right)^2 + \left(\sum_{i=1}^{4} l_i \sin\theta_i(t) - y^*\right)^2 - R^2 \geq 0 \qquad (8)$$

where

$\theta(t) = (\theta_1(t),...,\theta_5(t))^T$.

Performance Criterion

A performance criterion is now formulated to describe the lifting motion. Nubar and Contini's (1961) Principle of Optimality for Biomechanics states that a worker will minimize his physical effort by moving in a certain way, consistent with the task's constraints. This physical effort in performing a lifting task can be expressed as the worker's mechanical energy expenditure—a value that can be derived for this model. An approximation of the value is used as the performance criterion; by minimizing this criterion, we thus invoke the Principle of Optimality as stated by Nubar and Contini.

We can now note that Tichauer (1971) showed that the net moments induced about the joints of the body while performing a manual task are the major indices of injury during a task. Thus, to minimize the possibility of an injury while performing a task, it is only necessary to find the optimum performance of a task as defined by Nubar and Contini. This optimum performance (minimum mechanical energy expenditure) is directly proportional to the size of the net moments induced during a task.

Mechanical energy expenditure can be expressed as the time integral of the product of the force generated by the muscle in causing rotation and of its velocity in shortening. This approach was used by Chow and Jacobson (1971) to derive the criterion

$$\min \int_0^T \sum_{i=1}^{5} r_i |T_i(t)|^2 dt$$

where

$T_i(t)$ = the net torque acting at the *ith* link

r_i = a weighting factor for the *ith* link.

By similar methods, Nubar and Contini arrived at the same criterion as Chow and Jacobson.

To use the criterion for optimization, we first express the torques $T_i(t)$ in terms of the variables $\theta_i(t)$, $\dot{\theta}_i(t)$, and $\ddot{\theta}_i(t)$. From Equation 3,

$$\begin{aligned} T_i(t) = {} & T_i(\theta(t), \dot{\theta}(t), \ddot{\theta}(t)) \\ = {} & \sum_{j=i}^{5} \{ g\, m_i r_i \theta_i(t) + I_i \ddot{\theta}_i(t) \\ & + l_i (Fy_{i+1}(t) \cos\theta_i(t) \\ & - Fx_{i+1}(t) \sin\theta_i(t)) \\ & + m_i r_i (agx_i(t) \sin\theta_i(t) \\ & + agy_i(t) \cos\theta_i(t)) \} \qquad i = 1,...,5 \end{aligned} \qquad (9)$$

Define $\beta_i(t)$ as

$$\begin{aligned} \beta_i(t) = {} & g\, m_i r_i \theta_i(t) + I_i \ddot{\theta}_i(t) \\ & + l_i (Fy_{i+1}(t) \cos\theta_i(t) - Fx_{i+1} \sin\theta_i(t)) \\ & + m_i r_i (agx_i(t) \sin\theta_i(t) \\ & + agy_i(t) \cos\theta_i(t)) \qquad i = 1,...,5 \end{aligned}$$

Then by substituting T_5 into T_4, T_4 into T_3, etc., Chow and Jacobson's criterion can be written as:

$$\int_o^T (r_5\beta_5^2(t) + r_4(\beta_4(t) + \beta_5(t))^2 + r_3(\beta_3(t) + \beta_4(t) + \beta_5(t))^2 + r_2(\beta_2(t) + \beta_3(t) + \beta_4(t) + \beta_5(t))^2 + r_1(\sum_1^5 \beta_i(t))^2)dt$$

We note that the torque for the ankle, $T_1(t)$, includes all the other torques. For this study, we chose to ignore these other torques and minimized only the ankle torque since it includes the action of the others. Therefore, the performance criterion for this model can be written as

$$J(\theta(t), \dot{\theta}(t), \ddot{\theta}(t)) = \int_o^T T_1^2(\theta(t), \dot{\theta}(t), \ddot{\theta}(t))dt \quad (10)$$

Using Equations 1 and 2, $T_1(t)$ can be expressed in terms of the functions $\theta_i(t)$ as follows:

$$T_1(\theta(t), \dot{\theta}(t), \ddot{\theta}(t)) = \sum_{i=1}^{5} [m_i r_i g \cos\theta_i(t) + I_i\ddot{\theta}_i(t) + l_i \cos\theta_i(t) (Wt + \sum_{\substack{j=i+1 \\ i\neq 5}}^{5} m_j g)]$$
$$+ \sum_{i=2}^{5} m_i r_i \sum_{j=1}^{i-1} l_j \{\ddot{\theta}_j(t)\cos[\theta_i(t) + \theta_j(t)] - \dot{\theta}_j^2(t)\sin[\theta_i(t) + \theta_j(t)]\} \quad (11)$$
$$+ \sum_{j=1}^{4} l_j \sum_{i=j+1}^{5} m_i r_i \{\ddot{\theta}_i(t)\cos[\theta_i(t) + \theta_j(t)] - \dot{\theta}_i^2(t)\sin[\theta_i(t) + \theta_j(t)]\}$$
$$+ \sum_{i=1}^{4} l_i \sum_{j=i+1}^{5} m_j \sum_{k=1}^{j-1} l_k \{\ddot{\theta}_k(t)\cos[\theta_i(t)\theta_k(t)] - \dot{\theta}_k^2(t)\sin[\theta_i(t) + \theta_k(t)]\}$$

The Model

The mathematical model of a lifting task can now be stated as: determine twice continuously differentiable functions $\theta_1(t),...,\theta_5(t)$ that minimize the nonlinear function

$$J(\theta(t), \dot{\theta}(t), \ddot{\theta}(t)) = \int_o^T T_1^2(\theta(t), \dot{\theta}(t), \ddot{\theta}(t))dt \quad (12)$$

where $T_1(t)$ is given by Equation 11 and is subject to the following constraints:

$\theta_i(0) = A_i$	$i = 1,...,5$	-initial position of the body
$\theta_i(T) = B_i$	$i = 1,...,5$	-final position of the body
$\ell_{1,i} \leq \theta_i(t) \leq u_{1,i}$	$i = 1,...,5$	-bounds on the body's position
$\dot{\theta}_i(t) \leq u_{2,i}$	$i = 1,...,5$	-bounds on the body's velocity
$\ddot{\theta}_i(t) \leq u_{3,1}$	$i = 1,...,5$	-bounds on the body's acceleration

and $g_i(\theta(t)) \geq 0 \quad i = 1, 2, 3$

where g_1, g_2, and g_3 are given by Equation 8.

MODEL SOLUTION

The model has been reduced to determining functions that minimize a nonlinear function subject to linear and nonlinear inequality constraints. Such problems have their theoretical foundations in the classical Calculus of Variations (Smith, 1974). A necessary condition for a (weak) minimum, subject only to the end point conditions, is that a certain nonlinear differential equation, the Euler-Lagrange equation, be satisfied. However, this equation and the end point conditions constitute a two-point boundary value problem, the solution of which can be a difficult problem in itself. The introduction of inequality constraints further complicates the necessary conditions by requiring the use of slack functions and solution of the Euler-Lagrange equation along piecewise differentiable portions of the trajectory. For the problem treated in this research, such a method would be very difficult to implement.

A "direct" approach known as the Ritz method (Smith, 1974) is based on approximating the functions θ_i by a linear combination of basis functions Φ_j, which are twice continuously differentiable:

$$\theta_i(t) \triangleq \sum_{j=1}^{N} c_{ij}\Phi_j(t) \quad (13)$$

By substituting Equation 13 into Equation 11, we obtain the finite dimensional minimization problem of selecting the 5N-row vector of constant "parameters"

$$c \triangleq (c_{11}, c_{12}, ..., c_{1N}, c_{2N}, ..., c_{5N})$$

which minimizes the functional

$$\int_{o}^{T} T_1^2 (c\Phi(t), c\dot{\Phi}(t), c\ddot{\Phi}(t))dt \qquad (14)$$

In Expression 14, the assignment of T_1^2 denotes dependence of the original function in Equation 9 on the parameters c_{ij} and derivatives of $\Phi_j(t)$. Similarly, the constraints may be written in terms of the function $\Phi_j(t)$ and constraints c_{ij}:

$c\Phi(0) = A$		(initial position)
$c\Phi(T) = B$		(final position)
$l_1 \triangleq c\Phi(t) \leq u_1$	$0 \leq t \leq T$	(bounds on angles)
$\triangleq c\dot{\Phi}(t) \leq u_2$	$0 \leq t \leq \dot{T}$	(bounds on velocity)
$\triangleq c\ddot{\Phi}(t) \leq u_3$	$0 \leq t \leq T$	(bounds on acceleration)

For the moment, let us assume that the problem was unconstrained. Then a necessary condition for a minimum of J is that its gradient vanish at the optimal point $\hat{c}$:

$$0 = \nabla J(\hat{c}) \triangleq (\delta J/\delta c_{11}(\hat{c}), \ldots, \delta J/\delta c_{5N}(\hat{c}))$$

Elements of the gradient vector are easily computed using the chain rule:

$$\delta J/\delta c_{ij} = \int_{o}^{T} 2T_1(t)(\delta T_1(t)/c\Phi_j(t))(\delta\Phi_j(t)/\delta c_{ij})$$
$$+ (\delta T_1(t)/\delta\dot{\Phi}_j(t))(\delta\dot{\Phi}_j(t)/\delta c_{ij})$$
$$+ (\delta T_1(t)/\delta\ddot{\Phi}_j(t))(\delta\ddot{\Phi}_j(t)/\delta c_{ij})\,dt$$

The gradient can now be used to implement a descent algorithm for improving an initial estimate of the minimum while maintaining feasibility of the constraints. The actual technique chosen for this problem was dictated by the type of approximating functions chosen, as discussed in the next section.

Development of Constraints

The set of approximating functions is based on a function derived by Slots and Stone (1969). This function gives the displacement-time curve of the free joint of the body as:

$$\theta_i(t) = \theta_i(0) + \max(\theta_i)/2\pi\,[(2\pi t/T) - \sin(2\pi t/T)] \qquad i = 1,\ldots,5$$

where max (θ_i) is the maximum displacement of $\theta_i(t)$ for $0 \leq t \leq T$. In the model formulated, only $\theta_i(0)$ and $\theta_i(T)$ are known; $\max_t(\theta_i)$ is unknown. We can determine $\max_t(\theta_i)$ by the following relationship:

$$\max_t(\theta_i) = K_{1i}\,\theta_i(T) \qquad i = 1,\ldots,5$$

Another constant is needed to determine the time t^*_i at which max (θ_i) occurs. This time is determined by the condition

$$t^*_i = K_{3i}\,T \qquad i = 1,\ldots,5$$

where $0 \leq K_{3i} \leq 1$.

Finally, a constant was introduced as a scaling factor for the sine portion of the curve. The final form of $\theta_i(t)$ is given by

$$\theta_i(t) = \theta_i(0) + (K_{1i}\theta_i(T) - \theta_i(0))/2\pi[(2\pi t/K_{3i}T) - K_{2i}\sin(2\pi t/K_{3i}T)], \quad t \leq K_{3i}T$$

$$= \theta_i(T) - (K_{1i}\theta_i(T) - \theta_i(T))/2\pi\,[2\pi(t - K_{3i}T)/(T - K_{3i}T) - K_{2i}\sin(2\pi(t - K_{3i}T)/(T - K_{3i}T))], \quad t > K_{3i}T$$

A graph of this curve is shown in Figure 4a. The curve is composed of two straight lines and of two sine curves. If $t \leq K_{3i}T$, the straight line, $\theta_l(t)$, and sine curve, $\theta_s(t)$, are (Figure 4b)

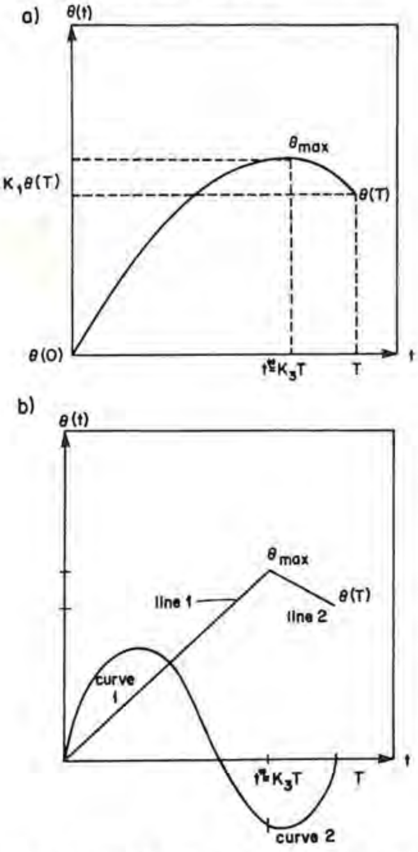

Figure 4. (Upper) Angular displacement-time curve; (lower) Decomposed angular displacement-time curve.

$$\theta_{l_i}(t) = \theta_i(0) + [(K_{1i}\theta_i(T) - \theta_i(0))/K_{3i}T]t$$

$$\theta_{s_i}(t) = -[K_{1i}\theta_i(T) - \theta_i(0))/2\pi]\,K_{2i}\sin(2\pi t/K_{3i}T)$$

If $t \geq K_{3i}T$, the line $\theta_{l_i}(t)$, and the sine curve, $\theta_{s_i}(t)$, are (Figure 4b)

$$\theta_{l_i}(t) = K_{1i}\theta_i(T) - (K_{1i}\theta_i(T) - \theta_i(T))/(T-K_{3i}T)\,(t-K_{3i}T)$$

$$\theta_{s_i}(t) = [(K_{1i}\theta_i(T) - \theta_2(T))/2\pi]K_{2i}\sin(2\pi(t-K_{3i}T)/(T-K_{3i}T))$$

By varying the constants, K_{1i}, K_{2i}, and K_{3i}, in this equation, we can find a family of curves for each angle (see Figure 5). The displacement-time curves were chosen as approximating functions because they reflect the specific type of motion being studied in this model. These curves also are very easy to bound in order to satisfy the constraints of the model.

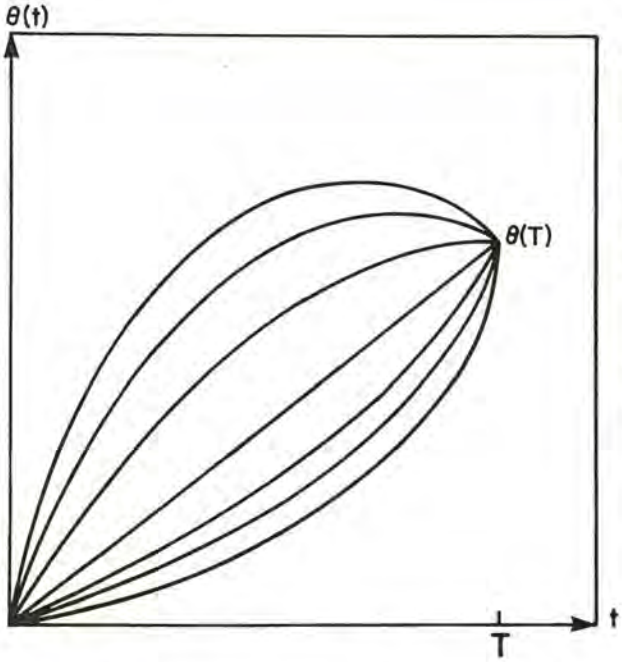

Figure 5. Sample family of displacement-time curves.

First, consider the equality constraints of the model, i.e., the initial and final positions of the body. These conditions are fulfilled automatically by the displacement-time curves due to their special construction:

$$\theta_i(0) = \theta_i(0) + \frac{K_{1i}\theta_i(T) - \theta_i(0)}{2\pi}\,\frac{2\pi\cdot 0}{K_{3i}T} - K_{2i}\sin\frac{2\pi\cdot 0}{K_{3i}T}$$

$$= \theta_i(0) + \frac{K_{1i}\theta_i(T) - \theta_i(0)}{2\pi}[0-0]$$

$$= \theta_i(0)$$

$$\theta_i(T) = K_{1i}\theta_i(T) - \frac{K_{1i}\theta_i(T) - \theta_i(T)}{2\pi}\,\frac{2\pi(T-K_{3i}T)}{T-K_{3T}} - K_{2i}\sin\frac{2\pi(T-K_{3i}T)}{T-K_{3i}T}$$

$$= K_{1i}\theta_i(T) - K_{1i}\theta_i(T) + \theta_i(T) = \theta_i(T)$$

The inequality constraints consist of three sets of bounds:

$$l_1 \leq \theta(t) \leq u_1 \qquad 0 \leq t \leq T$$
$$\dot\theta(t) \leq u_2 \qquad 0 \leq t \leq T$$
$$\ddot\theta(t) \leq u_3 \qquad 0 \leq t \leq T$$

We ignore the bounds on $\dot\theta(t)$ and $\ddot\theta(t)$, since it is assumed that the optimization will force $\dot\theta(t)$ and $\ddot\theta(t)$ within the prescribed bounds. The rationale for this assumption is that the slower a worker moves, the smaller the torques and forces he will exert about his joints. Thus, minimization of the performance criterion should also minimize the velocities and accelerations. This leaves only the bounds on the angles themselves to be considered:

$$l_1 \leq \theta(t) \leq u_1$$

These bounds can be affected for the displacement-time curves by bounding the constants $\{K_{1i}, K_{2i}, K_{3i}\}_1^5$ for each curve:

$$l_i/\theta_i(T) \leq K_{1i} \leq u_i/\theta_i(T)$$
$$-3\pi/2 \leq K_{2i} \leq \pi/2$$
$$0 \leq K_{3i} \leq 1$$

where

u_i = the maximum angle possible for the *ith* joint

l_i = the minimum angle possible for the *ith* joint.

These bounds arise naturally. Referring to Figure 4a, we can see that:

$$0 \leq t^*_i = K_{3i}T \leq T$$

implies the two conditions

$0 \leq K_{3i} T \leq T$
$0 \leq K_{3i} \leq 1$

To determine the bounds for K_{2i}, we want

$[(2\pi t/K_{3i} T) - K_{2i} \sin(2\pi t/K_{3i} T)] \geq 0; t \leq K_{3i} T$
implies $2\pi t/K_{3i} T \geq K_{2i} \sin(2 t/K_{3i} T)$

Now, $\sin(2\pi t/K_{3i} T) = +1$ at $t = K_{3i} T/4$
and $\sin(2\pi t/K_{3i} T) = -1$ at $t = 3K_{3i} T/4$

imply	$\pi/2 \geq K_{2i}$
and	$3\pi/2 \geq -K_{2i}$;
thus,	$-3\pi/2 \leq K_{2i} \leq \pi/2$.

A similar argument for $t > K_{3i} T$ shows that

$$-3\pi/2 \leq K_{2i} \leq \pi/2$$

Finally, a bound on K_{1i} will affect the bounds on $\theta_i(t)$ since K_{1i} changes the magnitude of the angles. We need only examine what happens at the point $t = K_{3i} T$ since the maximum magnitude of $\theta_i(t)$ will occur at the point. Thus

$$l_{1i} \leq \theta_i(K_{3i} T) = \theta_i(0) + (K_i \theta_i(T) - \theta_i(0))/2\pi(2\pi) \leq u_{1i}$$

implies $l_{1i} \leq K_1 \theta_i(T) \leq u_{ti}$
and $l_{1i}/\theta_i(T) \leq K_1 \leq u_{1i}/\theta_i(T)$.

This completes the analyses of the bounds on $\theta_i(t)$ using the displacement-time curves as an approximating function. The bounds on $\theta_i(t)$ are easy to obtain. In fact, they are simply bounds on the parameters, $\{K_{1i}, K_{2i}, K_{3i}\}_1^5$.

The constraint given in Equation 12, which defines a circular obstacle in the path of the worker, was implemented by the method of interior penalty functions (Fiacco and McCormick, 1968). The technique is based on modifying the objective function with an additional term, which is positive if the constraints are violated but zero if they are satisfied, and solving a sequence of minimization problems. The unconstrained problem has the form

$$\min_{c \in R^{5N}} \{ \int_0^T T_1^2(c\Phi(t), c\dot{\Phi}(t), c\ddot{\Phi}(t))dt + 1/r_i \sum_{K=1}^{3} \int_0^T \ln(-g_K(c\Phi(t), c\dot{\Phi}(t), c\ddot{\Phi}(t))dt\}$$

with $\{r_i\}$ a decreasing sequence of positive numbers. This does not alter the use of a gradient descent algorithm; it only changes the calculation of $\delta J/\delta c_{ij}$ to

$$\delta J/\delta c_{ij} = [\int_0^T 2T_1(t)[(\delta T_1(t)/\delta\Phi_j(t))(\delta\Phi_j(t)/\delta c_{ij}) + (\delta T_1(t)/\delta\dot{\Phi}_j(t))(\delta\dot{\Phi}_j(t)/\delta c_{ij}) + (\delta T_1(t)/\delta\ddot{\Phi}_j(t))(\delta\ddot{\Phi}_j(t)/\delta c_{ij})]dt + 1/r_i \sum_{K=1}^{3} \int_0^T 1/g_K (c\Phi(t), c\dot{\Phi}(t), c\ddot{\Phi}(t))\delta g_K (c\Phi(t), c\dot{\Phi}(t), c\ddot{\Phi}(t))/c_{ij}]dt$$

Thus, the problem, Equation 13, is transformed into a sequence of minimization problems involving a nonlinear objective subject to linear constraints.

Solution Procedure

The original model, as stated in Equation 12, consists of a nonlinear cost function subject to nonlinear equality and inequality constraints. By rewriting the angles $\{\theta_i\}_1^5$ as linear combinations of known functions, we have reduced the problem to minimizing a nonlinear cost function subject to linear constraints. Several algorithms exist to solve this type of problem. An algorithm developed by Murtagh and Sargent (1969) was chosen, since it has been found to be efficient for computer implementation. This algorithm is based on a rank one quasi-Newton descent with gradient projection techniques employed to satisfy constraints. At each iteration of the algorithm, the gradient is transformed into a vector that points towards a quadratic approximation of the objective. This direction is projected onto the tangent subspace of the constraints to yield a feasible direction of descent (i.e., one that does not violate the constraints). The Murtagh-Sargent algorithm is based on the following general formulation. Let F be a nonlinear differentiable function of the vector $x = (x_1, \ldots, x_n)^T$.

Consider the problem:

minimize	$F(x)$	
subject to	$a_i^T x - b_i \leq 0$	$i = 1, \ldots, r$
	$c_i^T x - d_i = 0$	$i = r+1, \ldots, m$
where	$a_i, c_i, x \in R^n$	
	$b_i, d_i \in R$	

At the beginning of each iteration, the following values are assumed to be known: the variables x, the gradient vector $g = \nabla F(x)$, an approximation H to the inverse Hessian, a set of integers indicating the active constraints, $I = i_1,...,i_K$, and a matrix whose columns are the normals to the active constraints $A^T = \{a_{i_1},...,a_{i_k}\}$. The Murtagh-Sargent algorithm is as follows:

0. Initialize x,g; Set H to the identity; Set $I = \{\phi\}$; Set $A = 0$

1. Compute the Lagrange multiplier: $\lambda = (AHA^T)^{-1} AHg$.

2. Compute an estimate of the maximum reduction in the cost function if one constraint is dropped from I:

$$\hat{\beta} = \max \{\beta_j = -1/2\, \lambda_j m_{jj}^{-1/2}, \lambda_j < 0\}$$

where m_{jj} is the *jth* diagonal element of $(AHA^T)^{-1} = M$

(For further explanation of the development of $\hat{\beta}$, see Gill and Murray, 1974).

3. Compute a search direction: $d = -H(g - A^T\lambda)$.

4. Test to terminate: $\|d\| < \epsilon_1$ and $\hat{\beta} < \epsilon_2$, stop

(i.e., if $\nabla F(x) \cong 0$ and no significant reduction in F can be attained by dropping a constraint).

5. Test to see if a constraint should be added or dropped.
   - i) If $|a_i{}^T x - b_i| < \epsilon_3$ and $a^T d > \epsilon_4$ and $i \notin I$, then add constraint i to active set (i.e., constraint i is almost violated and the present search direction moves toward it). Update A, I, and return to 1.
   - ii) If $\|d\| < \epsilon_5$ and $\hat{\beta}_j > \epsilon_6$, drop constraint j corresponding to $\hat{\beta}$ (i.e., $\nabla F(x) \cong 0$ but a significant reduction in F can be obtained by dropping constraint j). Update A and I and return to 1.

6. Search in the projected direction d:
   - i) Find the maximum feasible step-size to the first violated constraint k:
     $$\hat{\sigma} = \min_{k \notin I} \{\sigma_k | \sigma_k = (a_k{}^T x - b_k)/a_k{}^T d,\ a_k{}^T d > 0\}$$
   - ii) Find the optimal step-size
     $$\sigma^* = \text{argmin}\, \{F(x + \sigma d) \mid \sigma \in [0, \hat{\sigma}]\}$$

7. Update $x^* = x + \sigma^* d$, $g = F(x^*)$,
   $s = x^* - x$, $y = g^* - g$

8. Update H and M:
   let $z = s - Hy$
   if $z^T g < z^T y$: $H = H + zz^T/z^T y$;
   $M^* = M - MAz\,(MAz)^T/(z^T y + z^T A^T (MAz))$

   if $z^T g \geq z^T y$: $H = H + zz^T/\|z\|^2$;
   $M^* = M - MAz\,(MAz)^T/(\|z\|^2 + z^T A^T (MAz))$

Go to 1.

APPLICATION

The model and solution algorithm presented in the preceding sections were applied to solve a manual lifting problem. The problem can be stated as follows:

> A worker is required to lift a box weighing w kg and measuring s × h × l meters. The worker has to move between two points previously selected (set) in the workplace. The time for the entire motion (task) is T seconds. The worker can use one of two methods of lift: straight knees/bent back or bent knees/straight back.
>
> Determine the optimal lift: a lift that would be performed by an individual optimizing his performance consistent with task constraints.

Input Data

Assume that the worker is an average individual with anthropometric characteristics as those given in Table 1. Further, assume that the box is 0.25 m wide, 0.31 m long, and 0.36 m deep and weighs 6.1 kg. If handles are present on the box, assume they are on the side panel of the box, and, consequently, the worker would use them during the course of lifting. If no handles are on the box, assume the worker will place his hands around the lower part of the box. The initial and final configurations of the body are determined by the model. The bounds on the body angles are given in Table 2.

Initial Choice of Parameters

For each run of the model, there are 15 parameters, $C_{11},...,c_{53}$ to be initialized. For the first run of the model, the parameters were chosen at random, but for each subsequent run, the parameters selected were those found to be optimal by the previous run of the model.

When using the displacement-time curve approximation of the angles, it is only necessary to initialize 11 of the parameters. Due to the scissors

Table 1. Input data.

Body segment	Length	Equations for: Mass (bodymass = M)	Moment of inertia	Center of Mass
Ankle to knee	$0.41m = L_1$	$.046M = M_1$	$M_1L_1^2(.5565^2 - .438^2)$	$.433L_1$
Knee to hip	$0.43m = L_2$	$.105M = M_2$	$M_2L_2^2(.542^2 - .43^2)$	$.43L_2$
Hip to shoulder	$0.46m = L_3$	$.554M = M_3$	$M_3L_3^2(.83^2 - .66^2)$	$.66L_3$
Shoulder to elbow	$0.25m = L_4$	$.031M = M_4$	$M_4L_4^2(.54^2 - .43^2)$	$.43L_4$
Elbow to wrist	$0.23m = L_5$	$.025M = M_5$	$M_5L_5^2(M_5L_5^2 - .433^2)$	$.438L_5$
Hipspan = 0.35m				
Total body weight = 75 kg				

Table 2. Bounds on body angles.

Joint	Bounds
Ankle	$40 \leq \theta_1 \leq 90$
Knee	$90 \leq \theta_2 \leq 225$
Hip	$-10 \leq \theta_3 \leq 110$
Shoulder	$-95 \leq \theta_4 \leq 90$
Elbow	$-90 \leq \theta_5 \leq 90$

action of the legs, four of the parameters can be determined *a priori*. Note that the maximum displacement of any joint is given by:

$$\max \theta_i(t) = c_{i1}\theta_i(T)$$

For the first two links of the body (ankle to knee, knee to hip), the maximum angle is the final angle; thus, c_{11} and c_{21} are 1. Now the time at which the joint attains its maximum displacement is given by

$$t_{max} = c_{i3}T$$

and for the first two links of the body, this maximum is at time T; thus, c_{13} and c_{23} are 1.

Results

The model was run for three different lifts: (1) foot-to-shoulder lift, (2) waist-to-shoulder lift, and (3) foot-to-waist lift. These results are summarized in Table 3. For all three lifting tasks, it was assumed that handles were available on the side of the box and the worker would use the handles.

Foot-to-Shoulder Lift

For this lift, the worker is assumed to lift the box from his feet to his shoulders. The first run of the model assumed the worker had 3 sec to lift the box, and he used the bent knees/straight back method of lift. The lift cost the worker 144.82 $(N\text{-}m)^2$; a diagram of the motion is shown in Figure 6. When using the straight knees/bent back method, the lift cost 126.2 $(N\text{-}m)^2$. However, the straight knees/bent back method of lift required the box to be 8 in. off the floor initially because the worker could not reach it when it was sitting on the floor. Finally, the cost was higher when the worker was allowed only 2 sec rather than 3 to lift the box. He used the bent knees/straight back method, and the cost was 202.67 $(N\text{-}m)^2$.

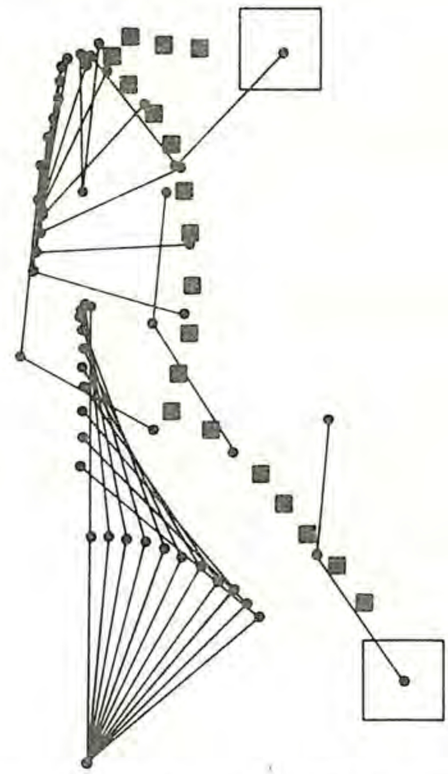

Figure 6. Foot-to-shoulder lift: 3 seconds.

Knuckle-to-Shoulder Lift

This lift was from the knuckles of the worker to shoulder height. Only the straight knees/bent back method of lift was studied in this case. The time for the lift was assumed to be 3 sec, and the cost to the worker was 126.2 $(N\text{-}m)^2$ (see Figure 7).

Table 3. Results of model applied to manual lifting problem.

Height	*Time*	*Method*	*Cost (N-m)²*		K_{ij}
Foot-to-shoulder	3	Bent knees	144.82	ankle:	$K_1 = 1$ $K_2 = -.046583$ $K_3 = 1$
				knee:	$K_1 = 1$ $K_2 = -.04708$ $K_3 = 1$
				hip:	$K_1 = 1.0767$ $K_2 = -.024449$ $K_3 = .12988$
				shoulder:	$K_1 = .81946$ $K_2 = .99218$ $K_3 = .77711$
				elbow:	$K_1 = 1.1032$ $K_2 = .38328$ $K_3 = .9154$
Foot-to-shoulder	2	Bent knees	202.67	ankle:	$K_1 = 1$ $K_2 = .062011$ $K_3 = 1$
				knee:	$K_1 = 1$ $K_2 = -.058234$ $K_3 = 1$
				hip:	$K_1 = 1.117$ $K_2 = -.037471$ $K_3 = .19999$
				shoulder:	$K_1 = -.8448$ $K_2 = .90232$ $K_3 = .77034$
				elbow:	$K_1 = 1.1032$ $K_2 = .34976$ $K_3 = .86448$
Knuckle-to-shoulder	3	Straight knees	126.2	ankle:	irrelevant
				knee:	irrelevant
				hip:	$K_1 = 1.0567$ $K_2 = .046247$ $K_3 = .057505$
				shoulder:	$K_1 = .83667$ $K_2 = .97658$ $K_3 = .68076$
				elbow:	$K_1 = 1.103$ $K_2 = .38021$ $K_3 = .88272$
Waist-to-shoulder	2	Straight knees	51.29	ankle:	irrelevant
				knee:	irrevelant
				hip:	$K_1 = 1.0996$ $K_2 = .0036607$ $K_3 = .049924$
				shoulder:	$K_1 = .86455$ $K_2 = .97934$ $K_3 = .71147$
				elbow:	$K_1 = 1.1032$ $K_2 = .3798$ $K_3 = .89587$
Waist-to-shoulder	1	Straight knees	41.33	ankle:	irrelevant
				knee:	irrelevant
				hip:	$K_1 = 1.1274$ $K_2 = .0057301$ $K_3 = .11048$
				shoulder:	$K_1 = .93765$ $K_2 = .93345$ $K_3 = .24416$
				elbow:	$K_1 = 1.1032$ $K_2 = .26838$ $K_3 = .84772$
Foot-to-waist	2	Straight knees	16.44	ankle:	irrelevant
				knee:	irrelevant
				hip:	$K_1 = 1.0108$ $K_2 = -.0005$ $K_3 = .016317$
				shoulder:	$K_1 = .88492$ $K_2 = .19282$ $K_3 = .85498$
				elbow:	$K_1 = .87315$ $K_2 = .093666$ $K_3 = .93093$
Foot-to-waist	1	Straight knees	19.24	ankle:	irrelevant
				knee:	irrelevant
				hip:	$K_1 = 1.0076$ $K_2 = .000086$ $K_3 = .031859$
				shoulder:	$K_1 = .86492$ $K_2 = .4711$ $K_3 = .60455$
				elbow:	$K_1 = .8736$ $K_2 = .2317$ $K_3 = .83163$
Foot-to-waist	2	Bent knees	75.567	ankle:	$K_1 = 1$ $K_2 = 1.5708$ $K_3 = 1$
				knee:	$K_1 = 1$ $K_2 = 1.5701$ $K_3 = 1$
				hip:	$K_1 = 1.07$ $K_2 = -.028304$ $K_3 = .18775$
				shoulder:	$K_1 = .9099$ $K_2 = .73853$ $K_3 = .77249$
				elbow:	$K_1 = .87315$ $K_2 = .2601$ $K_3 = .9178$
Foot-to-waist	1	Bent knees	68.504	ankle:	$K_1 = 1$ $K_2 = 1.4599$ $K_3 = 1$
				knee:	$K_1 = 1$ $K_2 = 1.5707$ $K_3 = 1$
				hip:	$K_1 = 1.0958$ $K_2 = -.015803$ $K_3 = .34997$
				shoulder:	$K_1 = .84898$ $K_2 = .69421$ $K_3 = .54533$
				elbow:	$K_1 = .83846$ $K_2 = .20384$ $K_3 = .88251$
Box constrained	3	Bent knees	9672.5	ankle:	$K_1 = 1$ $K_2 = 1.5429$ $K_3 = 1$
				knee:	$K_1 = 1$ $K_2 = 1.5708$ $K_3 = 1$
				hip:	$K_1 = 1.0256$ $K_2 = -.044699$ $K_3 = .35999$
				shoulder:	$K_1 = .89178$ $K_2 = .055493$ $K_3 = .7755$
				elbow:	$K_1 = .99035$ $K_2 = .34208$ $K_3 = .31239$

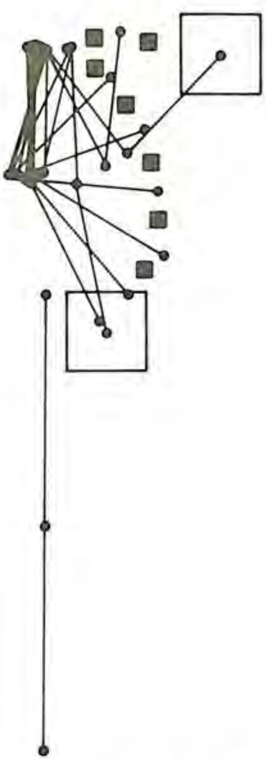

Figure 7. Knuckle-to-shoulder lift: 3 seconds.

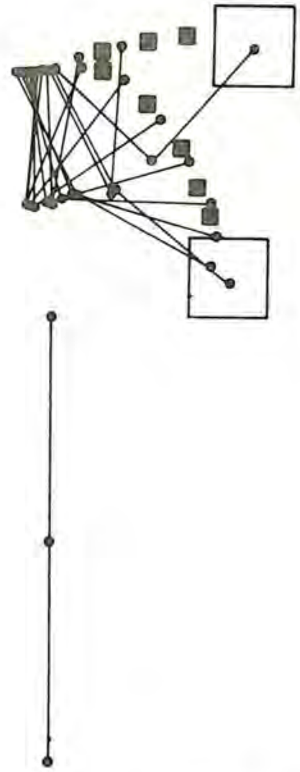

Figure 8. Waist-to-shoulder lift: 2 seconds.

Waist-to-Shoulder Lift

This lift was from the waist of the worker to shoulder height. Because the worker remained standing throughout this lift, only the straight knees/bent back method of lift was studied. For the first run, a time of 2 sec was assumed for the task and the cost to the worker was 51.29 $(\text{N-m})^2$; this lift is shown in Figure 8. The second lift assumed only 1 sec for the lift, and the cost was 41.33 $(\text{N-m})^2$.

Foot-to-Waist Lift

For this lift, the worker lifted the box from his feet to his waist; the box was initially 8 inches off the floor. With the use of the straight knees/back bent method of lift, the model was run four times allowing 1 and 2 sec for the task. The cost to the worker was 16.44 $(\text{N-m})^2$ and 19.238 $(\text{N-m})^2$, respectively. When the method of lift was bent knees/straight back, the cost was 75.57 $(\text{N-m})^2$ to lift the box in 2 sec (Figure 9) and 68.504 $(\text{N-m})^2$ to lift the box in 1 sec.

Constrained Lift

Finally, a special run of the model was attempted; this involved a foot-to-shoulder lift of 3 seconds, the bent knees/straight back method, and a sphere constraning the path was placed in the workplace. The cost to the worker was 9672.5 $(\text{N-m})^2$; a diagram of this lift is shown in Figure 10.

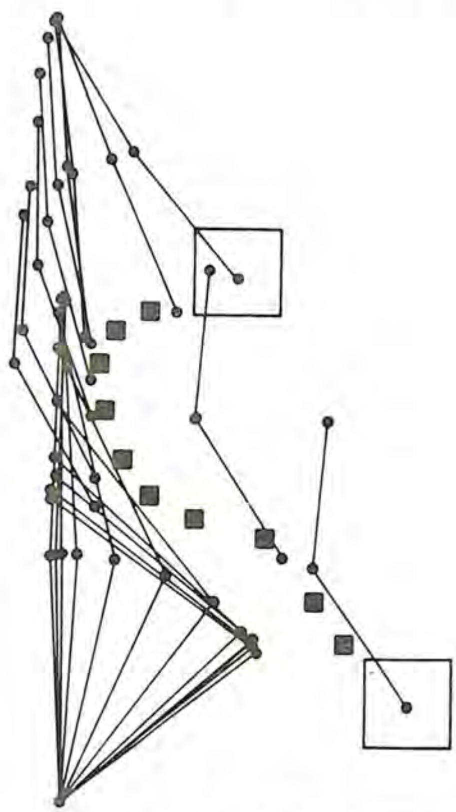

Figure 9. Foot-to-waist lift: 2 seconds.

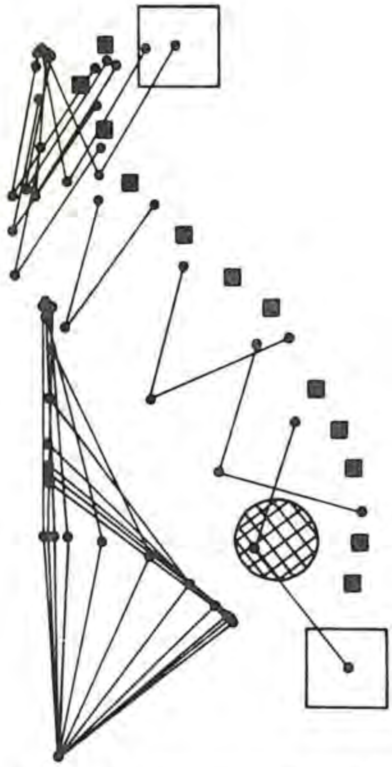

Figure 10. Constrained path lift.

Discussion

The paths of motions predicted by the model when using either method of lift (bent knees/straight back and straight knees/bent back) are consistent with the lifting literature. A box or an object is usually lifted by quickly bringing the weight of the object as close to the hips as possible, and then thrusting the object outward, and setting it down where desired. This is the action predicted by the model.

The time allowed for the lift was a significant factor in determining the cost of the task. For the foot-to-shoulder lift, using bent knees/straight back, an increase in time from 2 sec to 3 sec resulted in a decreased cost for the task. With the shorter time interval, the worker had to move faster throughout the entire lift, and this caused an increase in cost. The reverse is true for the waist-to-shoulder lift and the foot-to-waist lift: a decrease in time from 2 sec to 1 sec resulted in a decreased cost for the task. One possible reason for the decrease is that the actual distance the box is lifted is small enough that no savings result from moving the box close to the body as soon as possible and holding it there as long as possible, before thrusting it out — since this action results in more acceleration at critical parts of the lift. The choice of time for a task is critical in determining the cost of the task since it influences the speed and acceleration at which the task is accomplished.

For the foot-to-waist lift, the bent knees/straight back method of lifting costs more than the straight knees/bent back method. This reflects the fact that using the straight knees/bent back method does not induce any torques about the knee whereas the bent knees/straight back method does. Also, a comparison of the results for the two methods of lift is inconclusive for both the foot-to-shoulder task and the foot-to-waist task because, for the straight knees/bent back method, the box was not as low initially as it was in the case of the straight back/bent knees method.

The model was run on an IBM 370/165 computer using approximately 300 K bytes of storage. The number of iterations required for convergence for each lift (Table 4) was very dependent on the initial choice of parameters. Except for the first run of the model, each initial choice of parameters was selected as the optimum found by a similar run. For example, the initial choice for the 2 sec, foot-to-waist, back straight/bent knees lift was the optimum found by the 1 sec, foot-to-waist, back straight/bent knees lift. The convergence criterion for the model was that the change for each parameter value in one iteration be less than 0.005.

Table 4. Number of iterations for convergence.*

Number of iterations	*Task*
16	Foot-to-shoulder lift using bent knees/straight back and 2 sec
50	Foot-to-waist lift using straight knees/bent back and 1 sec
25	Foot-to-waist lift using straight knees/bent back and 2 sec
13	Foot-to-waist lift using bent knees/straight back and 1 sec
25	Foot-to-waist lift using bent knees/straight back and 2 sec
28	Waist-to-shoulder lift using straight knees/bent back and 1 sec
14	Waist-to-shoulder lift using straight knees/bent back and 2 sec

*Convergence criterion: $\| x_{i+1} - x_i \| \leq 0.0005$

Remark: The number of iterations required for convergence is not given for three tasks because these tasks were used to debug the model and changes were made in the model between iterations.

CONCLUSIONS AND COMMENTS

A crucial issue in the formulation of optimization models is the selection of an objective function. The objective function used in this study was the time integral of the square of the ankle torque (the total torque). Another objective that warrants further study is the time integral of the sum of the square of the ankle torque and the square of the net moment at the back. By weighting the square of the back's moment, a safe and less strenuous lift may result.

In this model, time is fixed so the worker cannot optimize his performance with respect to time. The optimum time to perform a lifting task is not known. Time, however, is a significant factor in determining the cost of a task and optimum body configurations during the performance of the task. Also, by optimizing over time, the model could yield sufficient information for the purpose of selecting appropriate work-rest schedules and of pacing task performance. Therefore, including time as a variable in the model seems to warrant further consideration.

The computing time required by the model is substantial. Reduction of the order of the model could decrease computing time considerably.

The model attempts to move the box as close to the body as possible throughout most of the lift and disregards the worker and the depth of the box. Constraints need to be formulated that would prevent the box from moving too close to the body.

The model as presented is limited to dealing with the constraints imposed by the physical characteristics of the workplace and of the worker. It would not be difficult, however, to expand the model and its constraint set to reflect the effects of heat, illumination, and confined spaces on the overall performance of the task. By including such effects in the model, a very complete analysis of the lifting task could be made.

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COMPUTER MODELS IN MANUAL MATERIALS HANDLING

R. F. Goldman

The preferred definition of ergonomics, for this reviewer, is that it is the process whereby one simultaneously examines both the physical, physiological, and psychological requirements associated with the task and the physical, physiological, and psychological characteristics of the worker. The object is to compare these requirements and capacities and then attempt to adjust any mismatch. This ergonomic approach seems equally valid in attempting any computer prediction of manual materials handling.

Prediction of the weight that can be lifted can logically be made simply by considering the amount of muscle of the workman; the more muscle, the greater the weight that can be lifted. However, this simple prediction becomes confounded by the technique for assessment of muscle. If one uses classic somatotyping where muscularity, as the second component of body composition, is assessed in terms of muscle definition, it is difficult for an observer to establish a meaningful correlation between the weight that can be lifted and mesomorphy. The unsatisfactorily low correlation suggests selection of a more appropriate worker characteristic to match the desired task characteristic. This emphasizes the need for careful selection of both work and worker characteristics to produce a matched set of necessary and sufficient features.

This review attempts to outline a few prediction models for physical, physiological, and psychological aspects of manual materials handling and also to suggest the appropriate worker characteristics that should be measured in attempting to assess the degree of match between requirements and capacity.

When starting with the physical weight of the load to be moved, mesomorphy, as indicated above, is an inadequate worker characteristic. Although it is tempting to use 4 kg/cm^2 of muscle cross-sectional area, as projected in the literature, for the force that can be exerted, determination of muscle cross-sectional area is hardly simple enough for an industrial survey of work capacity. If, however, one assumes that the population of workers is relatively homogeneous with respect to the proportion of muscle in their total body, then it is clear that a heavier man should have a greater weight lifting capacity than a lighter man. As shown in Figure 1, this appears to be true for world class weight lifters and, presumably, given the assumption of a relatively homogeneous worker population, should hold for industry. Thus, a simple prediction can be made that a man should be able to lift a given percentage of his body weight.

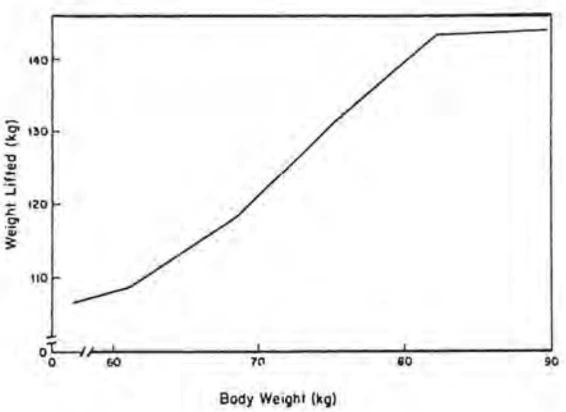

Figure 1. The relationship between "explosive" strength, as demonstrated in the "press" weight lift, and body weight for world record weight lifters.

However, as shown by Asmussen et al. (1959) in studies on children from 7 to 16 years of age, muscle power is also related to body height, in an exponential manner. Accordingly, one might develop an argument that height, rather than weight, should be the variate. Asmussen et al. (1959) also suggest that age, body type, and state of sexual development must be responsible for the larger part of the deviations, which usually amount to ± 15% to 20% of the mean in measures of muscle strength per se. Asmussen and Heeboll-Nielsen (1961) measured adult isometric muscle strength of 360 men and 250 women, aged 15 to 60 years, for 25 different muscle groups. This same group has also published, in detail, specific measurements and devices recommended for use in testing muscle strength (Asmussen et al. 1959). Again, as in the children, a positive relationship between height and strength was demonstrated, but because of large individual scattering in strength due to other factors and the relatively narrow range of body heights in the usual populations available for study, no exact relationship could be calculated. As Asmussen and his group have pointed out, if two persons are geometrically similar, it is to be expected that their muscle strength, measured directly as maximum pulls or pushes in kilograms, depends on the cross-sectional areas of the muscle. The latter, again, must be proportional to the linear dimension squared. Therefore, when strength is measured as a maximum torque (i.e., kilograms times centimeters), it must vary as the linear measures to the third power. This theoretical relationship can be confirmed in children with fair accuracy, although most often strength increases a little more with height than expected from the simple cubic relationship, probably because taller children are also older than shorter ones (Asmussen et al., 1959).

On average, the women in Asmussen's sample were about 92% of the height of the men; one could expect, therefore, that the pull or push strength for women would be $(92\%)^2$ that of men, or about 85%. However, this was not the case. In general, the average value for all women over age 20 in their sample was only 58% to 66% of men of the corresponding age. If a correction was made for the shorter body height of the women, the women's muscular strength was still only 70% to 80% that of men of the same age. Another characteristic feature is that muscle strength apparently reaches maximum sooner in women, but then begins to decrease at an earlier age than in men. In general, it seems safe to use the "industry standard" reference value, i.e., that women can exert roughly 60% the strength of men, as a reasonable prediction.

In addition to these factors, whether one measures the dominant (e.g., usually right) or nondominant side of the body will also have an effect. Thus, if materials are to be lifted with one hand and if the lift is to be made by the hands and arms, one should subtract 5% for the weaker side. If the strength is to be provided by the trunk, some 8% should be subtracted; if the strength is to be provided from the lower extremities and if the weaker side is to be involved, about 10% must be deducted. (Asmussen and Molbeck, 1958). These values, again, were derived in children. In adults, the tendency exists for the dominant side to be stronger (Heeboll-Nielsen, 1964), but there are so many exceptions to this rule that one cannot place much significance in it. The standard deviation of the difference, in percentage of the stronger side, varies from 5% to 14% and must be evaluated according to results from individual tests. Generally speaking, in the case of the upper extremities, the difference between the stronger and weaker sides is larger for adults than for children. However, in view of the overall variability, it seems safe at the present time to use the same relationships for adults as for children.

As indicated by the preceding discussion, an extensive data base exists for the maximum isometric strength that can be exerted by adults and children. Some representative values, in kilograms (data from Asmussen and Heelboll-Nielsen, 1961), for a 175-cm tall man are:

	Muscle test		
Age, yr	*Horizontal pull*	*Horizontal push*	*Leg extension (1 leg)*
25	49.1 kg	32.9	310.3
35	49.8	32.1	311.9
45	48.2	31.5	295.5
55	45.8	30.6	262.8
65	42.9	30.0	216.8
S.D.	± 14%	± 20%	± 17%

In general, taking maximal isometric strength for young men at age 23 as the 100% baseline for muscle strength of the arms, strength remains at this level until about age 37, then falls to about 95% of baseline at age 50 and to 92% by age 60. For leg strength, taking the level at age 21 as 100%, leg strength increases to 105% at age 30 and then falls slowly, reaching 103% at age 40, 95% at age 50, and about 85% at age 60.

If one establishes, as a working hypothesis subject to further validation, that a single weight lifted in industry should not exceed 50% of maximum strength value, one can use these physiological maxima, with appropriate adjustments for height, sex, age, nature of object to be lifted (awkwardness, one hand versus two hand), height, and nature of lift (leg or arm work, chest level or overhead), to develop a theoretical prediction base. Some coefficients for such task-based models have been suggested by Drury and Pfeil (1974) and others. Drury recently reviewed a number of these predictive models (Drury, 1975), and one of these might be used as a base into which the preceding physiological characteristics could be inserted and then subjected to validation studies. Such an approach would synthesize the task base with the physiological strength models. Validation of such a model can be obtained, after appropriate adjustment, by comparing the results with reports of studies evaluating actual maximum acceptable weights of lift (Drury, 1975). Certainly, such an approach should produce a better recommendation than the 1964 conclusion of the International Labour Office that 40 to 50 kg is a maximum load for males.

Detailed physiological data do not yet appear to exist for dynamic muscle strength. Thus, the data base for repetitive lifting, in contrast to the maximum single isometric lift discussed above, is not available. However, a high correlation has been shown between an individual's static and dynamic strength (Asmussen et al., 1965) and data exist on decrement and recovery with repeated maximal muscle contractions (Caldwell, 1970), so such modelling could be pursued.

Taking a completely different approach, if one knows the physical work demanded by a given task (i.e., weight lifted times height of lift) in kilogram-meters, one can estimate the equivalent cost to the worker of the task if one can estimate his efficiency. A number of investigators have studied both arm work (hand cranking) and bicycling (leg work); their results are shown in Figure 2, in terms of the energy that fit young men expend for the horse power produced. The gross efficiency, in percent at a given work load, is given in Figure 3 and suggests that, at lower levels of work demand, the physical efficiency falls off rather dramatically; however, as work begins to approach difficult levels for leg work, a plateau is reached at about 20% gross efficiency (i.e., including the resting metabolic heat production in the calculation of total energy expended). For arm/hand work, no plateau appears, although the peak efficiency indicated in the figure is about 14%.

Table 1 provides relationships between the physical work of a task (expressed in kgm, ft-lb and watt units) and the metabolic cost (kcal/min, $\dot{V}O_2$/min and watt) derived assuming a 20% efficiency, along with some statements of what these metabolic costs equate to in terms of demands and some corresponding oxygen costs of actual measured activities for "normal" men. Note that, as the resting metabolic demands (central nervous system, respiration and circulation, and gut oxygen requirements) become a smaller fraction of the total work, the 20% efficiency estimate is quite a reasonable one. Thus, the oxygen cost of manual materials handling can be estimated and compared with the worker's maximum oxygen uptake capacity.

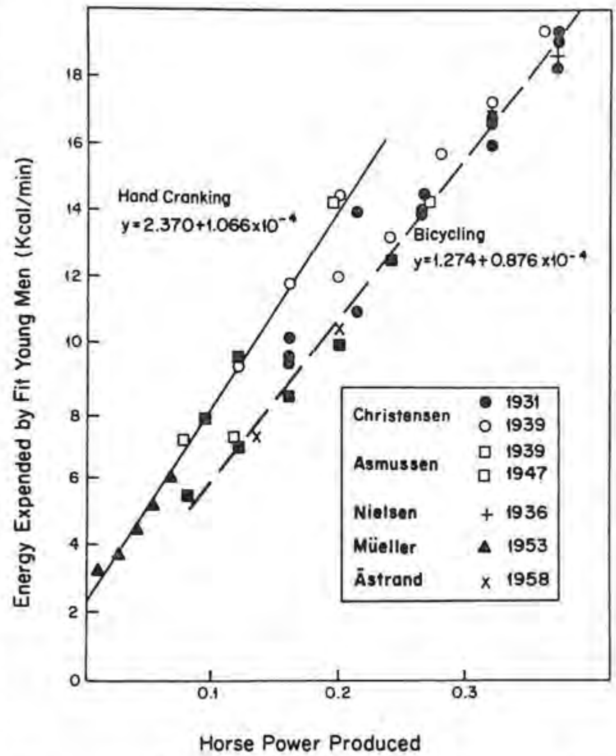

Figure 2. Energy expanded by fit young men (kcal/min) as a function of the horsepower produced by hand cranking or bicycling.

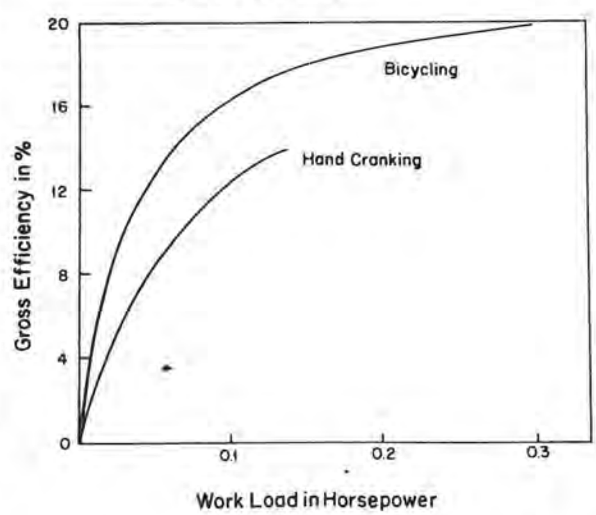

Figure 3. The gross efficiency for hand cranking or bicycling as a function of the relative workload expressed in horsepower.

In addition to the physical cost of the weight lifted per se, the rate at which the weight must be moved comes into play. This is obvious in terms of lift work, where the number of repetitions per

Table 1. A comparison of physical work equivalents and their theoretical energy cost, assuming an efficiency (η) of 20%, with the measured energy costs determined for fit young men.

Physical work			*Energy cost, η = 20%*			*Activity*	*MET*	*Measured "normal" men*			*H.P.,*	*Efficiency,*
kgm/m	*ft-lb/m*	*watt*	*kcal/m*	*watt*	*$\dot{V}O_2$, l/min*		*50 kcal/ m^2-hr*	*$\dot{V}_E$, l/min*	*$\dot{V}O_2$, l/min*	*HR, b/min*	*η=20%*	*η − %*
13	93	2	.15	10	.03	Circ + resp.-rest	0.1					
26	185	4	.30	21	.06	C.N.S.	0.2					
38	278	6	.45	31	.09	Circ + resp.-work	0.3					
64	463	10	.75	52	.15	Gut at rest	0.5					
102	741	17	1.2	84	.24	Basal (sleep)	0.8					
128	926	21	1.5	105	.30	Sit at rest	1.0					
192	1389	31	2.25	157	.45		1.5					
224	1621	37	2.63	183	.53	Very light	1.75	10	0.5	< 75	0.05	
256	1852	42	3.00	209	.60		2.0					
320	2316	52	3.75	262	.75	Walk 2.75 mph	2.5					
384	2779	63	4.50	314	.90		3.0					
416	3010	68	4.88	340	.98	Light	3.25	20	1.0	75-100	0.1	15.7
448	3242	73	5.25	366	1.05		3.5					
512	3705	84	6.00	419	1.20		4.0					
640	4632	105	7.50	523	1.50	Moderate	5.0	35	1.5	100-125		
864	6253	141	10.13	707	2.03	Heavy 1-hr $\dot{V}O_2$ max	6.75	50	2.0	125-150	0.2	20
1056	7642	173	12.38	864	2.48	Very heavy	8.25	65	2.5	150-175		20
1280	9263	209	15.00	1047	3.00	$\dot{V}O_2$ max, exhaustion after 10 min	10.00	85	3.0	> 175	0.3	20
1600	11579	262	18.75	1308	3.75	Exhausting	12.50				0.35	
2202	15933	360	25.8	1800	5.16	2-mile record anaerobic	17.2				0.5	

minute simply is a multiplier of the total physical work required; but it is less obvious in walking with a weight where, since theoretically there is only translation of load rather than lift work, no physical work is involved. A number of physiologists have addressed this question and shown that, in fact, weight is lifted across the center of gravity of the body with each step; but this aspect will not be discussed in the present review. However, as one begins to exceed the level of oxygen utilization that can be replenished during work and accumulates an oxygen debt culminating eventually in largely anaerobic work, the time a given speed can be maintained falls off dramatically. This is shown clearly in Figure 4. Indeed, where oxygen demand is the physiologically limiting feature, the suggested maximum work capacity of fit young men can be derived in terms of the duration of effort and the liters of oxygen consumed per minute for physical work to be carried out, as shown in Figure 5. A graph of the maximum and the sustainable work (i.e., 50% of max $\dot{V}O_2$) as a function of age, sex, and physical condition is shown in Figure 6, using data reported by Åstrand (1960).

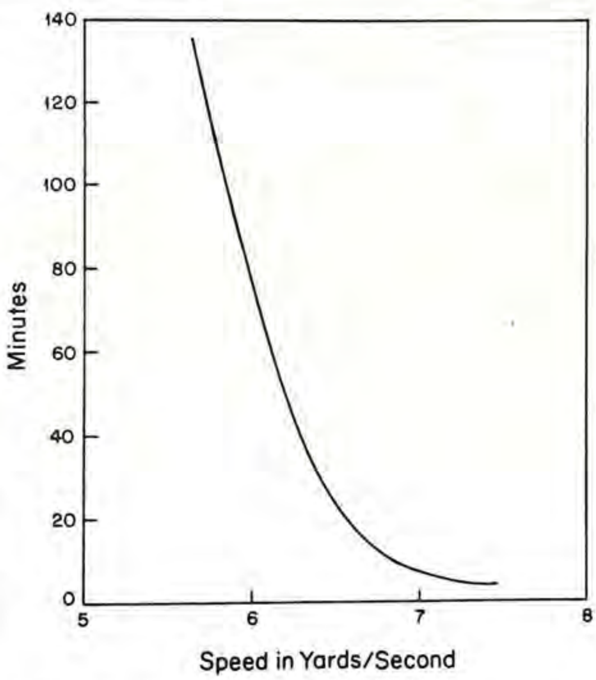

Figure 4. A relationship between endurance and work rate, as demonstrated by the speeds and elapsed times for Olympic track records.

In all of these, we assume that the weight involved is that of the body. Other studies have shown that load weight, if carried reasonably well balanced and close to the center of gravity of the body, is carried at no additional cost per kilogram over that of the body weight per se (Goldman and Iampietro, 1962). However, weight carried further from the center, i.e., on the head as in some native populations, in the hands, in trouser "cargo" pockets (unpublished), or on the feet, exerts increasing costs. Weight on the head is equivalent to 30% more than weight carried on the back; weight on the hands 210% more than body weight;

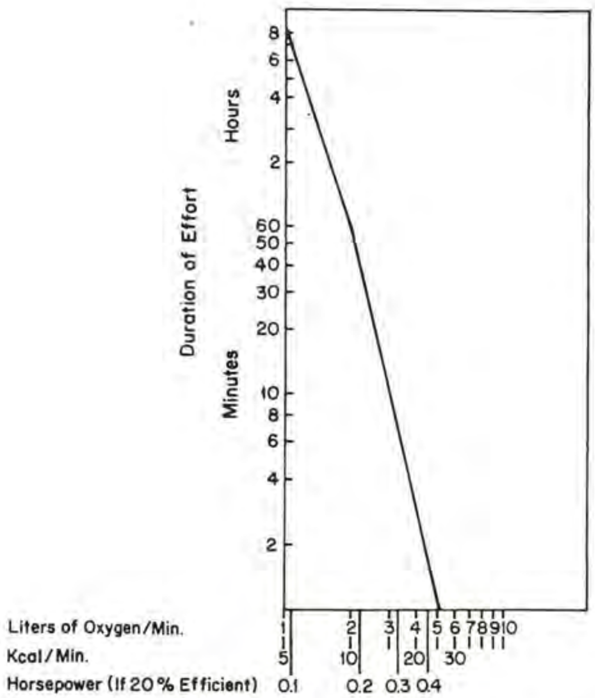

Figure 5. Suggested maximum work capacities of fit young men. The duration for which a given effort can be sustained is presented as a function of the work rate.

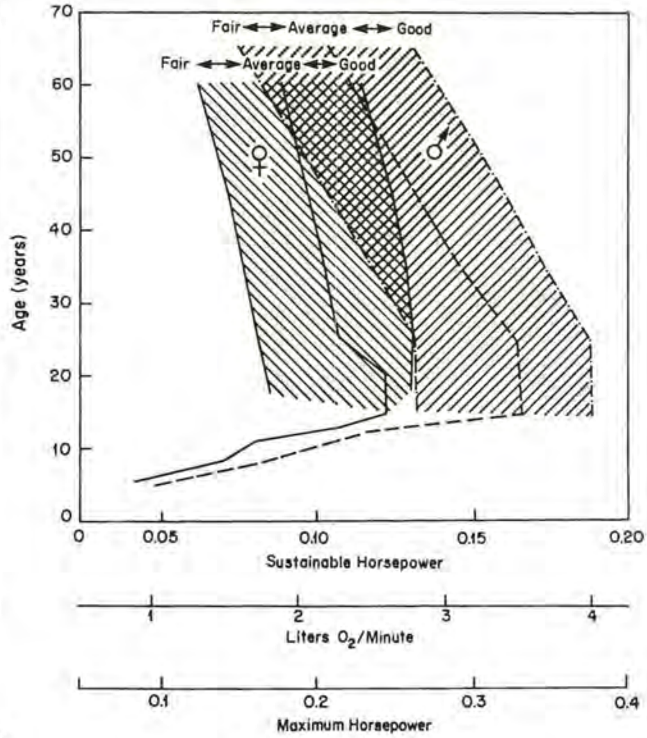

Figure 6. The maximum and sustainable maximum horsepower producible by males and females from 10 to 60 yr of age as a function of physical condition; data from Åstrand (1960).

and weight on the feet between 300% and 500% of that of weight on the back as a function of the speed of progression (Soule and Goldman, 1969). Thus, the physical weight of the load, the height of lift, the speed of lift, and the nature of the physical load, whether static work or dynamic work is required, etc., all are involved in predictive models for physical aspects of weight that can be lifted.

An example of a more complete, oxygen-cost-based model of a load moving task for back packing of loads across a variety of terrains at any conceivable speed has been presented by Givoni and Goldman (1971) and modified by Pandolf et al. (1976). The formula they derived empirically presents energy cost prediction (M in watt) as a function of body weight (W in kg), load weight (L in kg), speed (V in m/s), grade (G in %), and terrain (η*) as:

$$M = 1.5(W) + 2.0(W+L)(L/W)^2 + \eta(W+L)(1.5V^2 + 0.35VG) \quad (1)$$

The first term is the resting energy cost of the body (i.e., for a 70-kg man, 1.5 × 70 = 105 watt); the second is the cost for standing with a load and is proportional to the ratio of load to body weight, squared; and the last term is the energy cost for moving with the load.

The predicted energy cost can be compared with acceptable values to determine the degree of difficulty of the task and, if it is hard work, to estimate how long it can be carried out. The energy cost, predicted by Equation 1 in watts, can be converted to kcal/min (watt × 0.86/60), and the probable duration of the work can be estimated, for 20- to 25-yr-old young men of average military fitness, by comparing the energy cost with Figure 5 (e.g., a calculated energy cost of 700 watt × (0.86/60) = 10 kcal/min, which corresponds to a level of work that can reasonably be sustained for about 60 min by such individuals). With the use of the liters of oxygen to kilocalories per minute correspondence given in Figure 5 (i.e., 5 kcal/min = 1 l of VO_2/min), duration estimates can be adjusted as a function of age, sex, and physical condition by reference to Figure 6.

As an example of the utility of such modeling, the probable progression rate (V) can be estimated for young men of average fitness, as a function of load

*For a given W, L, V, and G, the cost on a treadmill is taken as η=1; other terrain coefficients are expressed as ratios: e.g., blacktop road = 1, light brush = 1.3, heavy brush = 1.5, sand = 2.1, etc. (Pandolf et al., 1976, and Soule and Goldman, 1972).

and terrain, using 7 kcal/min as their probable, motivated, hard-work level (Hughes and Goldman, 1970) that will be sustained for periods of 2 to 3 hours or more. This work rate, which represents about 45% of the maximum oxygen uptake of such individuals, compares with the 40% to 50% of uptake generally considered as sustainable for hard work in general (Soule et al., 1975).

Having presented physically and physiologically based models of manual materials handling, the more recent work on psychologically based models remains to be mentioned. As indicated above, the work capacity demands of a work task can be estimated from physical considerations, and the energy cost demanded from the worker in accomplishing the task can be measured. However, the corollary of the physical prediction model presented is that, except for relatively minor individual variability, a given task for two individuals of equivalent weight will require the same energy cost. In effect, any measurement of the cost should merely confirm the energy cost demanded by the physics of the situation since, given equivalent training, the efficiency of the individual workmen will be quite comparable. Thus, in the practical case, what determines the level at which an individual will work comfortably is not the task demand, but its relationship to his individual capacity.

Techniques exist for measuring the maximum work capacity of an individual. Maximum oxygen uptake can be measured directly or estimated from extrapolation of heart rate and oxygen uptake measurements at less strenuous levels (Åstrand and Rhyming, 1954; Goldman, 1971; and Pandolf and Goldman, 1975), but even these are not practical measurements in an industrial setting. Heart rate is readily measured; maximum heart rate as a function of age can be estimated for men as 220 minus age in years. As an upper *maximum,* a man should not work at more than 60% to 70% of his maximum heart rate. Indeed, the German work physiologists recommended that the "work pulse", i.e., the difference between heart rate on the job and at rest, should not exceed 30 beats per minute.

This close relationship between heart rate and work demand suggests that heart rate can be used as a measure of the relative work stress. Borg (1970) developed a category scale of subjectively "Reported Perceived Exertion" (RPE) ranging from 6 to 20, with 7 identified as very, very light, 9 as very light, 11 as fairly light, 13 as somewhat hard, 15 as hard, 17 as very hard and 19 as very, very hard. The subject, during work, is simply presented with a chart showing this RPE scale and points to the number corresponding to his perception of the relative difficulty, *for him,* of the work. The specific number selected was originally proposed (Borg, 1970) as corresponding closely to heart rate divided by 10; e.g., an RPE of 13 should correspond to a heart rate of 130 b/m.

Although many researchers have failed to confirm the RPE/heart rate relationship, a number of us find the RPE scale quite useful, particularly when used to question "local?" muscle sensations as well as "central?" cardiopulmonary and "overall?" sensations (Ekblom and Goldbarg, 1971; Henriksson et al., 1972; Kay and Shephard, 1969; and Pandolf and Noble, 1973). A striking example of the information available from these differentiated RPE responses occurred in a study on load moving by carts. No physiological differences could be observed in measured heart rates or oxygen consumption, but local RPE evaluations clearly differentiated between fatigue induced by pushing with the hands up on the handle versus that with hands down (Haisman et al., 1972). An experimental model to describe the RPE levels associated with different types of physical activity has recently been suggested by Kinsman and Weiser (1974) and additional modeling is being developed (Pandolf et al., 1975).

In conclusion, a variety of approaches to modeling manual materials handling exist in addition to the empirical, task-based ones. Physical, physiological and, within the last decade, psychological frameworks exist for assessing task demands in manual materials handling, for evaluating these in terms of worker capacities, and for identifying potential factors limiting capacity or duration of such work.

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CHAPTER 3. SUMMARY

Chapanis (1959) in a classic statement observed:

Do not underestimate man. Many physical scientists seem to approach human experimentation with the attitude, "Well, after all, man is nothing more than . . ." You can add your own ending to the sentence, since the words have changed over the years and will continue to change. A couple of hundred years ago it was the vogue to say that man is nothing more than a system of complicated levers and pneumatic tubes (the nerves and blood vessels) which carry energizing liquids. Fifteen or so years ago, it was popular to say that man is nothing but a servo. Now it is the thing to say that man is nothing but an information-handling channel. Call man a machine if you will, but do not underestimate him when you experiment on him. He's a non-linear machine; a machine that's programmed with a tape you cannot find; a machine that continually changes its programming without telling you; a machine that seems to be especially subject to the perturbations of random noise; a machine that thinks, has attitudes, and emotions; a machine that may try to deceive you in your attempts to find out what makes him function, an effort in which, unfortunately, he is sometimes successful.

If we are modeling rather than measuring, we make assumptions at our peril and constantly need to validate our models to maintain some faith in their accuracy. The complaint raised at the symposium about biomechanical models was that they referred to headless lifters with but one arm and with their knees tied together. If our only purpose in modeling was practical predictions, then validity coefficients would be sufficient answer to this criticism. In this sense, Chaffin's models would be the most useful because of their greater number of validations.

We can, however, use a model at many levels. Fish uses biomechanics to ease data collection in that movie film replaces the complex apparatus required for in vivo measures of intra-discal pressure. At the other end of the scale, models can draw our attention to those factors and relationships that are important in the real world. Chaffin's use of human strengths and Ayoub and El-Bassoussi's use of Tichauer's biomechanical lifting equivalent are two obvious examples. Finally, the model can begin to explain *why* effects happen rather than merely show that they do. Herein lies the strength of the Muth, Ayoub, and Gruver model. It is an expensive model to work with even with its simplifying assumptions, but the whole idea of optimization models could advance us to the point in the study of work that biochemical models have in the study of a single contraction.

In terms of inputs and outputs, all the models are concerned with the same set of factors. How should one lift? What are the effects of the container and workplace geometry on the maximum weight that can be safely lifted? Their predictions are one basis for the intervention strategies of Chapter 4, such as how to train for manual materials handling and how to design containers.

While extensions of the models are needed, it should not be overlooked that extensions of the data base are also required. The debt to Dempster; Drillis; Contini; Slote and Stone, etc., is large in biomechanics. The only current civilian strength data base comprehensive enough for Chaffin's models is for children. Goldman's original data base was largely young, fit males although this has now had considerable extension. The fact remains that the more rigorous and comprehensive the model, the greater the need for a comprehensive data base. Such research is long on time and effort and short on academic kudos, which says more about the narrowness of academic criteria than about how society should invest its money. Even in data base collection and analysis, the models can help allocate resources by measuring their own sensitivity to accuracy of input data.

One final observation is that these models, when they are done correctly, represent a detailed analysis of how manual materials handling tasks stress the body. This is again the industrial engineer and ergonomist's preoccupation with the 99% of work cycles that are successful. If we want to reduce injuries rather than just reduce work stress, perhaps we should also analyze the situations where the biomechanical model misses its footing or where its hand slips on the container.

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CHAPTER 4
FACTORS AFFECTING PERFORMANCE

INTRODUCTION

What do we need to know to design an efficient and safe manual materials handling task? Our limiting human subsystems and models of performance give an enormous range of data we really should take into account in design. As with any design problem, however, we can and must have some priorities on the factors included in our design if we are to do anything other than marvel at the complexity of human performance. The topics reviewed in this chapter cut across models and across subsystems. They were chosen, with the aid of the Herrin, Chaffin and Mach (1974) report, as being a priori the most useful topics to cover. This in itself represents a form of editing. As it turned out, when one workshop at this symposium was asked to consider which factors were needed in any future standard, the ones in Chapter 4 ranked high on the list.

Human factors engineers have long summarized their position with regard to system improvements by stating that the three aspects for potential change are the worker, the task, and the environment. Even those are not mutually exclusive as an adaptive organism such as the worker will change physically and mentally with changes in the job. Even the task is really only a convenient label for an ill-defined subset of the environment.

With these caveats in mind, we can roughly classify the papers in this chapter. Ayoub et al., and Shealy take very different aspects of the worker—the physical and the attitudinal—and try to distill out the essential ingredients. How few strength data can you put into a human/task model and still obtain reasonable predictive validity? How can you find constants and concepts within the messy field of risk-taking? Both, as would be expected, note that you cannot ignore the task in assessing the individual.

The biomechanical modeling bears fruit in Ayoub's sequence of related case studies in container design. This paper shows the statics of design and how not to overstress the muscular/skeletal system. It is followed by two papers on the dynamics of design, one oriented towards the task (Burse) and the other towards the environment (Kamon). They both answer the questions of how much work and how often. Predictive formulae and tables for work/rest cycles and thermal load and even observations on the effects of airborne hazards are presented.

The summary at the end of this chapter attempts to integrate this knowledge into a more applicable form.

MODELING OF LIFTING CAPACITY AS A FUNCTION OF OPERATOR AND TASK VARIABLES

M. M. Ayoub, R. D. Dryden, J. W. McDaniel, R. E. Knipfer, and F. Aghazadeh

INTRODUCTION

Frederick Taylor (1911) advocated that the right man for the right job is the way to achieve an efficiency that will result in lasting benefits to society. Chaffin and Maulis (1969) observed, on the other hand, that there is not a single "right" man for each job; but there are "wrong" men for particular jobs. He also noted that "Management can never be a science until the decisions that are made in an organization are based on measurable quantities." It is to this end that this research was directed—namely, that of providing the appropriate combination of measurable quantities and the predictive models for screening purposes for employee placement and job engineering.

Poulsen (1970) pointed out ". . . rules for what workers handle manually vary widely from country to country, and the way in which these rules have been laid down very often depends on national laws and traditions." The majority of countries have reported some types of provisions applying to women, children, and young persons. These classes of workers are often broken down into age groups, the maximum authorized load being specified for persons in each group. In contrast to the position regarding women and young workers, very few countries have adopted legislation or regulations applying to adult male workers. Research to date has simply not provided the generalized tools and techniques appropriate for widespread application.

Many authors and researchers (Jones, 1971, 1972; Brown, 1971; Snook and Ciriello, 1972) have noted that the best protective action in materials handling is to know human limits and operate within them. The major difficulty in applying such a philosophy arises from the inability to state a firm policy concerning a permissible weight due to varying operating conditions of the man-task-environment system, namely individual operator characteristics, task variables, load characteristics, and work practices (Herrin et al., 1974).

Maxwell (1957) observed that there are two kinds of strain resulting from weight handling—immediate strain, which requires immediate medical treatment, and cumulative strain, whose cause is more difficult to determine. The avoidance of conditions contributing to cumulative strain is important because of the time and expense of its treatment and cure.

The determination of a person's operative burden may be critical. Snook and Irvine (1969a) noted that if a person is overloaded, he will suffer from an exhaustive fatigue; if he is insufficiently loaded, he will suffer from boredom. One must also differentiate between strength and work capacity. Not enough research has been devoted to establishing work capacity. Strength implies what an individual can do in a single trial, whereas work capacity implies what an individual can do for an extended period of time.

Background

The problems associated with manual materials handling may be approached by two somewhat opposing philosophies. The first would entail setting lifting standards so low that literally everyone would be able to perform the lifting task repetitively for extended time periods without incurring either fatigue or bodily injury. The second approach, if followed to its extreme, would entail relaxing the lifting standards in an attempt to optimize the working efficiency at the expense of the worker's safety. Either of these approaches, if carried to these extremes, would be unsatisfactory. It has been pointed out by Grandjean (1969) that, when considering lifting and carrying of loads, working efficiency and prevention of damage to the spine should both be considered.

The proficiency with which we are capable of placing individuals on the proper job and/or designing jobs to conform with individual differences and limitations is indicated, in part, by safety statistics. These statistics claim that manual handling tasks represent the principle source of compensable work injuries. Many of these injuries are believed to occur because man exceeds or is asked to exceed his physical capabilities.

Useful information has been provided by research concerning the maximum permissible weight of lift. The studies to date, such as Switzer (1962), Snook and Irvine (1967), and Snook et al. (1970b), have contributed significantly to the usefulness of experimental lifting data by their innovative experimental procedures and reporting technique of group work capacity. Their efforts did not, however, yield a predictive lifting model, which would have been very desirable. The next logical step, then, is to develop models that may be easily and inexpensively applied to determine the group work capacity classifications to which a particular individual should be assigned.

Purpose

The modeling approach utilized herein for predicting a permissible weight lift for the individual has the potential for removing the employee placement decision from an opinion (based on simple observation, general rules of thumb, or on the average worker) to a more rational placement decision. The use of rules of thumb and averages is discouraged as a basis for determining what is a reasonable and safe task for an individual to perform. The use of an average value to estimate the lifting capacity of an individual has the possible disadvantage of overexerting half the working population, while penalizing the remaining half of the population. It has been said that the average worker does not really exist. Whether or not this statement is true does not detract from the advantages associated with properly estimating what is safe for the individual rather than making judgments based on averages or rules of thumb, which might possess less of a scientific base.

METHODS AND PROCEDURES

Before any discussion of methods used to determine and model lifting capacity, it is essential to present the variables that may potentially affect the capacity of an individual for handling materials. Since manual materials handling can be viewed as a man/task environment system, the variables can be categorized under these system components: the individual, the task, and the environment (Table 1). The experiments reported in this paper concentrated on investigating the effects of certain individual and task variables on the lifting capacity of industrial workers. Four separate sets of experiments were performed: the first, by McDaniel (1972), concentrated on lifting from floor-to-knuckle height; the second, by Dryden (1973), concentrated on lifting from knuckle height to shoulder height; the third, by Knipfer (1974), concentrated on lifting from shoulder height to reach height; and the fourth, by Aghazadeh (1974), in which he used the data by McDaniel, Dryden, Knipfer, as well as generated additional data to further modify the models. Aghazadeh also included the effects of frequency of lift and box size variables in his capacity models. The first three experiments will be referred to in the paper as the first generation experiments. The experiments by Aghazadeh will be referred to in the paper as the second generation experiments.

Table 1. Variables affecting manual materials handling capacity.*

Individual Variables

Physical: Age, sex, anthropometry, strength, mobility, motor, and psychomotor function.

Physiological: Physical work capacity, aerobic capacity, anaerobic capacity, metabolic capacity, and circadian tolerance.

Psychological: Motivation, emotional status, job satisfaction, attitudes towards work.

Task Variables

Load handled: Weight, size, shape, distribution of the load, ease or difficulty of coupling, the degree of shift of the load in the container.

Workplace layout: Degree of movement required, obstacles, postures dictated, distances moved and direction of movement.

Level of demand: Both static and dynamic—frequency of lift, duration of lift, accelerations and velocities of lift, shift duration, degree of precision, degree of body members involvement.

Environmental Variables

Environmental conditions include heat and cold stress, noise and vibration factors, lighting, toxic agents, traction, stability of the work platform.

* Modified from Drury and Pfeil, 1973; Herrin, Chaffin, and Mach, 1974; Chaffin and Ayoub, 1975 .

First Generation Experiments

Tasks

The task associated with these experiments was of a physical nature—namely, a dynamic lifting task. The subject lifted a tote box 305 × 255 × 230 mm high (12 × 10 × 9 in.) from floor to his standing knuckle height; from his knuckle-to-shoulder height through a range of 510 mm (20 in.); and from shoulder height to reach height through a range of 510 mm (20 in.). These heights and ranges were selected for three reasons:

1. Individual differences could be minimized by always adjusting the initial height to the knuckle height, or shoulder height, of the subject and then

requiring the performance of a lift involving 510 mm (20 in.) for each subject (regardless of his or her height).

2. The selection of these heights was made on the basis of the muscle groups involved in the performance of the lift. These lifting ranges required the combination of back-leg-arm muscle groups.

3. These particular heights and ranges are specified in the literature and were used by researchers when performing different types of experiments, such as Snook and Irvine (1967), Snook et al. (1970b), and Switzer (1962). The results of this work could then be compared and evaluated with other research data using this same standard height and lifting range to determine its consistency or lack of consistency.

After the subject had lifted the tote box to the proper height, it was placed on a table that lowered the box back to the initial height of lift (floor, knuckle height, shoulder height). The task, therefore, only involved the lifting operation and did not involve lowering the tote box. From experimental data, it has been determined that the amount of weight an individual can lift varies somewhat from the amount that the same individual can lower for repetitive-type tasks (Snook, 1971).

Experimental Procedure

The experimental procedure consisted of the measurement of anthropometric, strength, and physiological parameters shown in Table 2, as well as the maximum acceptable weight of lift determined from the lifting experiments. The various measurements were taken in such a manner or sequence that the subjects recovered from fatigue or shortness of breath before continuing with the next measurement. The determination of the duration and number of rest allowances between measurements was made by evaluating and comparing the subject's heart rate with that of his or her resting heart rate measured before conducting the tests.

The experimental procedure with respect to the lifting task being performed was selected to be a modified psychophysical technique. The major concern of these experiments was the determination of the lifting capacity of individuals and the development of a predictive model for the maximum permissible weight of lift for the three heights and ranges of lift. Snook (1971) further commented after his lifting experiments that, with enough repetition and experimental control, psychophysical measurements can become more reliable than many physiological or performance measurements.

The lifting procedure associated with these experiments allowed the subject to subjectively adjust the amount of weight he or she could lift repetitively for an 8-hr workday, based upon his estimate of his working capacity, fatigue, and endurance. The subject was instructed to adjust his workload to the maximum amount he could perform without strain or discomfort and without becoming tired, weakened, overheated, or out of breath. The weight of the tote box was to be added to or subtracted from until the maximum weight the subject could handle repetitively was determined. The frequencies of lift were four, six, and five times/min from floor-to-knuckle, knuckle-to-shoulder, and shoulder-to-reach height, respectively. The duration of the lifting portion of the experiment was set at a maximum of 45 min, a time determined to be sufficient from similar previous lifting studies (Snook and Irvine, 1967, 1969; McDaniel, 1969).

Each subject started the first phase of the lifting experiment without knowing the exact weight in the tote box and adjusted the weight at will and continued lifting for 20 min with the minimum of visual cues concerning the exact weight of the box and time that had elapsed. Each subject's watch was removed before starting the experiment. The weight of the tote box was checked at each 5-min

Table 2. Operator variables measured for each of the Texas Tech experiments.

Physical parameters	*Floor-to-knuckle*	*Knuckle-to-shoulder*	*Shoulder-to-reach*
Height of subject	X	X	X
Weight of subject	X	X	X
Sex of subject	X	X	X
Reciprocal ponderal index (RPI)	X	X	X
Arm strength	X	X	X
Back strength	X	X	X
Leg strength	X	X	X
Shoulder strength			X
Hip extension strength			X
Horizontal push strength			X
Static endurance	X	X	X
Dynamic endurance	X	X	X
Fitness index (FI)	X	X	X
Percent fat		X	X
Thigh circumference			X
Chest circumference		X	X
Biceps circumference		X	X
Forearm circumference		X	X
Abdominal circumference			X
Upper arm length		X	X
Age of subject		X	X
Arm torque		X	X
Back torque		X	X
Leg torque		X	X
Shoulder torque			X
Hip extension torque			X
Forearm grip length		X	X
Heart rate		X	X
Oxygen consumption rate		X	X

interval without interrupting the task. After 20 min, the subject was allowed to take a 10-min break, after which the experiment continued.

Each subject started the second phase of the experiment without knowing the amount that he or she finally selected at the end of the first phase of the experiment. The initial weight of the tote box at the start of the second phase of the experiment was whichever weight (heavy or light) was not used to start phase one of the experiment. If, for example, the subject started phase one with the heavy box, then phase two was started with the light box. This procedure was followed to minimize the effect or bias resulting from the initial weight of the box. The maximum permissible weight of lift was determined by averaging the weights being selected at the end of the first and second 20-min lifting intervals.

Subjects

The experiment was conducted with the use of 135 subjects—67 females and 68 males. Two males and one female were rejected before testing because of safety considerations involving their personal health. The subjects were recruited from industry with the exception of 40 subjects used for the first range of lift. These 95 subjects were workers whose jobs involved lifting each day. The experiment also consisted of a personal interview concerning each subject's employment. During this screening process, it was necessary to further limit the female population by dropping seven additional subjects whose jobs did not involve lifting. Subjects ranged between 20 and 50 yr of age. During the subject selection process, consideration also was given to the subjects' heights, weights, and ages.

Variables

Two general types of variables were measured during this experiment. The first type included variables to be used directly and evaluated as to their appropriateness to be used in predicting the maximum permissible weight of lift; these are operator variables. The second type of variables was measured and used for the purpose of making subjective judgments concerning the subject's performance. These variables were not used directly for modeling purposes.

The input variables (operator variables that were considered for modeling purposes) are listed in Table 2 by each height and range of lift.

Heart rate and oxygen consumption were measured for two reasons other than modeling. The first was for safety considerations, allowing the experimenter to note immediately any indications of excessive exertion. The second, used in retrospect, was to evaluate subjectively the subject's performance and his ability to estimate an appropriate work exertion level. Detailed descriptions of these variables with the measurement procedure are discussed by McDaniel (1972), Dryden (1973), Knipfer (1974), and Aghazadeh (1974). The variables were used independently, in combinations, and as cross products and quotients. This was made possible by the transgeneration variable option of the stepwise regression computer program that was used.

Second Generation Experiments

Aghazadeh (1974) conducted new experiments and also used the data by McDaniel (1972), Dryden (1973), and Knipfer (1974) to develop new predictive models. The Aghazadeh experiments followed the same procedures outlined above and concentrated on simplifying the models by reducing the number of variables and by including the effects of the frequency of lift and box size variables in the models.

His approach was to establish the relationship between the lifting capacity for lifting from floor-to-knuckle height and the remaining two levels of lift—namely, lifting from knuckle height to shoulder height and from shoulder height to reach height. These relationships are presented in the results section. Thus, the task was then reduced to developing a predictive model for only one range of lift — the floor-to-knuckle height — from which the other two levels can be predicted based on the relationships between the levels of lift. In addition, Aghazadeh included two task variables — frequency of lift and box size — in the second generation experiments. The frequencies selected were one, three, and four lifts/min and the box sizes were 305 × 255 × 230 mm high (12 × 10 × 9 in.), 455 × 255 × 230 mm high (18 × 10 × 9 in.), and 610 × 255 × 230 mm high (24 × 10 × 9 in.).

RESULTS

First Generation Experiments

Predictive Models

The maximum weight lifted by each subject for each level of lift showed correlations with several individual characteristics. The highest correlations are shown in Table 3. These characteristics were considered for the development of lifting capacity predictive models. These models were formulated using a Stepwise Regression Program. It was decided that a comprehensive data evaluation should be performed using three subject groups. The first group was used for modeling, the second group for selecting the "best" model from the alternatives provided by group one, and the third group to test the accuracy of the "best" model selected by using group two. The final decision was to divide the subject population among the three groups by generally using 10 subjects to build a group of models, to use 5 additional subjects to select a "best" model from the available models, and to use the remaining 5 subjects to test the "best" model from the available models. The groups are unique in that subjects used in one group are not included in either of the two other groups. The best model was selected based on the least average error of prediction. The average error of prediction was calculated by averaging the ratio of the absolute value of the difference between the predicted and observed lifts divided by the observed lift.

Table 3. Correlation coefficients between maximum acceptable weight of lift (MAWL) and selected variables.

Physical parameters	*Floor-to-knuckle*	*Knuckle-to-shoulder*	*Shoulder-to-reach*
Sex	.548	.865	.801
Leg strength	.747	.618	.607
Back strength	.740	.590	.661
Static endurance	.712	.622	.724
Arm strength	.697	.780	.671
Weight	.551	.573	.518
Arm torque	—	.776	.672
Forearm circumference	—	.685	.685
Back torque	—	.638	.663
Biceps circumference	—	.622	.537
Leg torque	—	.611	.581
Forearm grip length	—	.540	.579
Chest circumference	—	.508	.580
Percent fat	—	−.731	−.569
Horizontal push strength	—	—	.746
Shoulder strength	—	—	.605

This procedure was used for all three ranges of lift yielding several models as shown in Table 4.

Ridge Analysis

The original combined male/female model selected for prediction of acceptable lift from shoulder to reach height was:

$$\text{Predicted maximum acceptable weight of lift} = 36.44 \times \text{sex} + .107 \text{ horizontal push} - .56 \text{ shoulder strength.}$$

Although this model performs well, it is difficult to convince users of its validity because intuitively it is difficult to accept that as the shoulder strength increases, the capability would decrease. This is the result of the negative coefficient of the shoulder strength factor in the model. Such results are not unique. Saunders (1973) pointed out that regression curve fitting works in a straightforward manner as long as there is no correlation between the independent variables. Hoerl and Kennard (1970), in developing Ridge Regression Theory, report that "in multiple regression it is shown that parameter estimates based on minimum residual sum of

Table 4. Best models from the three lifting ranges.

Male model	*Female model*	*Combined model*
	Floor-to-knuckle height (McDaniel, 1972)	
Predicted lift = − 172.3599 + 0.0220607 × Height^2 − 2.72867 × Static endurance^2 + 0.0209696 × Reciprocal ponderal index × Arm strength + 0.0534346 × Reciprocal ponderal index × Back strength − 2.51346 × Fitness index/Dynamic endurance^2	Predicted lift = − 24.02682 + 0.19362 × Reciprocal ponderal index^2 + 0.00607224 × Arm strength × Leg strength	Predicted lift = 11.93388 − 1.1024 × Back strength + 0.15811 × Reciprocal ponderal index^2 + 0.00458322 × Back strength^2 − 8.80718 × Static endurance^2 − 0.09552 × Sex × Fitness index + 0.06007 × Height × Reciprocal ponderal index + 0.0231265 × Reciprocal ponderal index × Leg strength − 0.00021627 × Back strength × Leg strength − 0.027092 × Leg strength × Static endurance + 0.11092 × Static endurance × Fitness index
	Knuckle-to-shoulder height (Dryden, 1973)	
Predicted lift = 0.0 + 0.82766 × Chest circumference + 0.55885 × Dynamic endurance	Predicted lift = 0.0 − 1.47347 × Height × Fitness index/1000 − 0.31199 × Reciprocal ponderal index × Static endurance + 1.22804 × Percent fat × Fitness index/1000	Predicted lift = 24.12120 + 0.37912 × Sex* × Dynamic endurance
	Shoulder-to-extended-reach height (Knipfer, 1974)	
Predicted lift = 4.91337 + 0.19746 × Back strength − 0.01733 × Shoulder strength + 0.42917 × Age	Predicted lift = 15.07131 + 0.34346 × Weight + 0.83999 × Dynamic endurance + 0.33545 × Forearm circumference	Predicted lift = 5.225 × Sex* + 0.00494 × Shoulder strength + 0.1944 × Horizontal push strength

*For sex: 1 for females, 2 for males.

squares have a high probability of being unsatisfactory, if not incorrect, if the prediction vectors are not orthogonal."

With the model above, the intercorrelation of the four included variables for all cases, male and female, is high. High correlation among the independent variables indicates that results of their use in regression may cause difficulty. Hoerl and Kennard described a relatively new technique (Ridge Regression) for adjusting values of correlation coefficients; Benrey (1973) applied it to some laboratory and practical problems. The application of ridge analysis was used to develop the models for lifting from shoulder-to-reach height only. Models for all three ranges are combined in Table 4 for ease of comparison.

Predictive capabilities of the models for the three ranges of lift are presented in Table 5. For the floor-to-knuckle height model, the average error of prediction was 8.8% for the male model, 6.8% for the female model, and 15% for the combined male-female model. The largest error ratios were 16.7%, 8.9%, and 29%, respectively. Figure 1 shows the observed and predicted maximum acceptable weight of lift for test subjects for the male-female model in this range.

Similarly, the predictive capabilities for the second range of lift — the knuckle-to-shoulder height — are presented in Table 5. The average error ratios for the male model, female model, and combined male-female model are 9.9%, 14.9%, and 15.4%, respectively. The largest error ratios were 16.5%, 21.8%, and 30.7%, respectively. For the

Table 5. Summary of test statistics for all three lifting ranges.

Error ratio/ square error	*Male*	*Female*	*Combined*
Floor-to-knuckle height, models with transgenerations (McDaniel, 1972)			
Average error ratio	0.0878	0.0683	0.1498
Average square error	35.0000	7.9200	44.5800
Largest error ratio	0.1673	0.0896	0.2906
Correlation	0.9921	0.9187	0.9336
Knuckle-to-shoulder height, transgenerations (Dryden, 1973)			
Average error ratio	0.0985	0.1486	0.1540
Average square error	43.0520	20.1073	37.0877
Largest error ratio	0.1651	0.2176	0.3071
Correlation	—	—	0.9438
Shoulder-to-reach height (Knipfer, 1974)			
Average error ratio	0.1747	0.2536	0.1555
Average square error	70.7654	44.3480	31.8017
Largest error ratio	0.3313	0.4598	0.4410
Correlation	0.8327	0.6600	0.9242

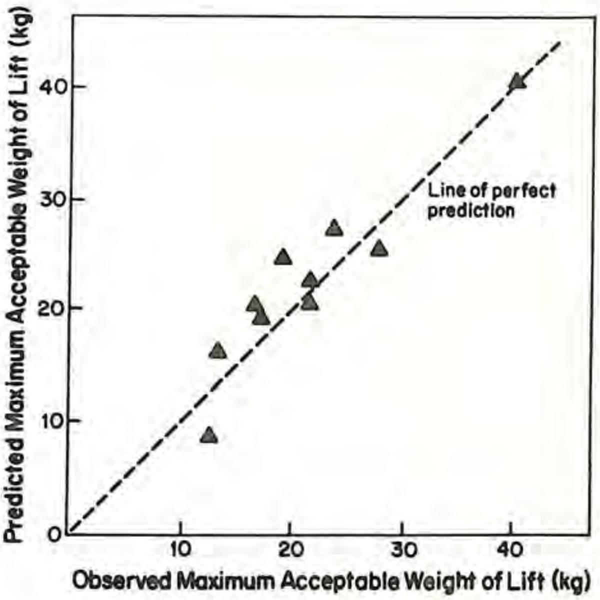

Figure 1. Observed and predicted maximum acceptable weight of lift for male and female test subjects (floor-to-knuckle height; combined male-female model).

floor-to-knuckle height and knuckle height to shoulder height, the separate male and female models show lower average error ratios and largest error ratios. Figure 2 shows the observed and predicted maximum acceptable weight of lift for the test subjects for the male-female model in this range.

The predictive capabilities of the models for the upper range of lift were lower than the models for the lower range of lift. The average error ratios for male, female, and combined male-female models were 17.5%, 25.4%, and 15.5%, respectively. The largest error ratios for the same models were 33%, 46%, and 44%, respectively. These values indicate that the predictive capabilities of the models for the high range of lift are poorer than those for the lower range of lifting. Figure 3 shows the observed versus the predicted maximum acceptable weight of lift for the shoulder-to-reach height range of the male-female model.

Second Generation Experiments

Predictive Models

With the use of the relationship between the levels of lift mentioned earlier and shown in Figure 4, a simplified model was attempted. The approach also incorporated the effects of frequency of lift and box size on the maximum acceptable weight of lift obtained through the second generation experi-

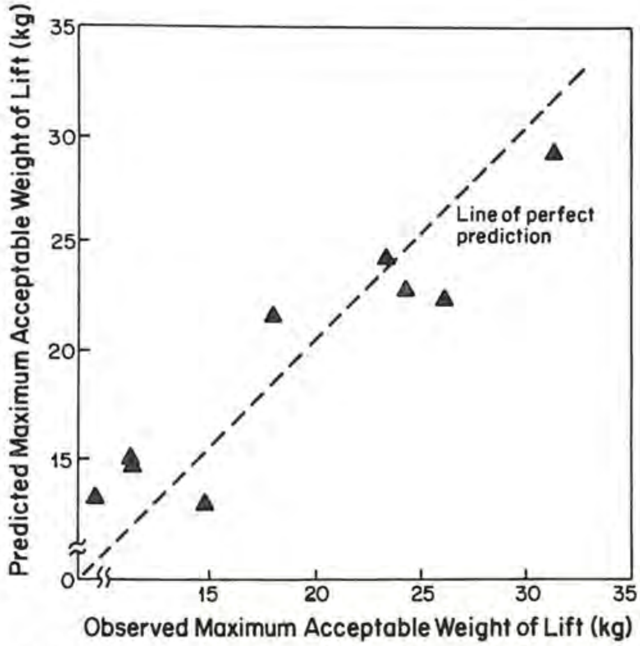

Figure 2. Observed and predicted maximum acceptable weight of lift for male and female test subjects (knuckle-to-shoulder height; combined male-female model).

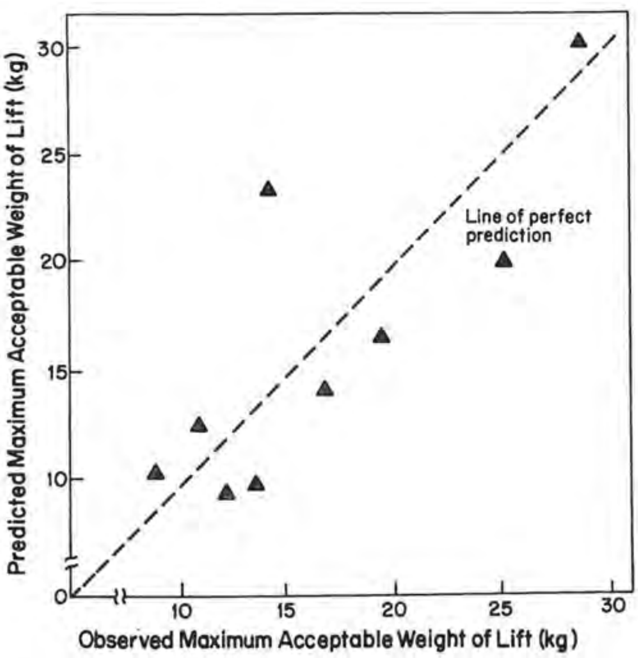

Figure 3. Observed and predicted maximum acceptable weight of lift for male and female test subjects (shoulder-to-reach height; combined male-female model).

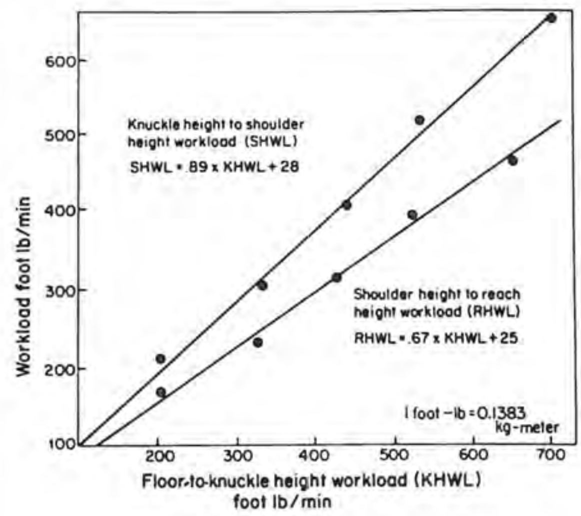

Figure 4. Relationship between workload for lifting from floor-to-knuckle height and lifting from knuckle-to-shoulder height and shoulder-to-reach height.

ments. Figures 5 and 6 show the effect of changing frequency of lift and box size on lifting capacity. Therefore, the predictive model can now consider fewer operator variables and some task variables. The model selected was in a form similar to that reported by Drury and Pfeil (1973):

Predicted maximum accepted weight of lift
$$= (C_1 S + C_2)C_3$$

C_1, C_2 = factors dependent on the frequency and level of lift

where

$$S = \frac{(\text{back strength} \times \text{leg strength})}{1000}$$

C_3 = factor dependent on box size

From the experimental data obtained, Tables 6 and 7 were developed to use in the model. These tables give C_1, C_2, and C_3.

Example: For lifting from knuckle height to shoulder height at frequency of three lifts/min with a box 18 × 10 × 9 in. high, the following factors can be selected from Tables 6 and 7.

$C_1 = 1.66$ $C_2 = 17.9$ $C_3 = .90$

If the operator strengths are:

leg strength 165 lb (75 kg)
back strength 170 lb (77.3 kg)

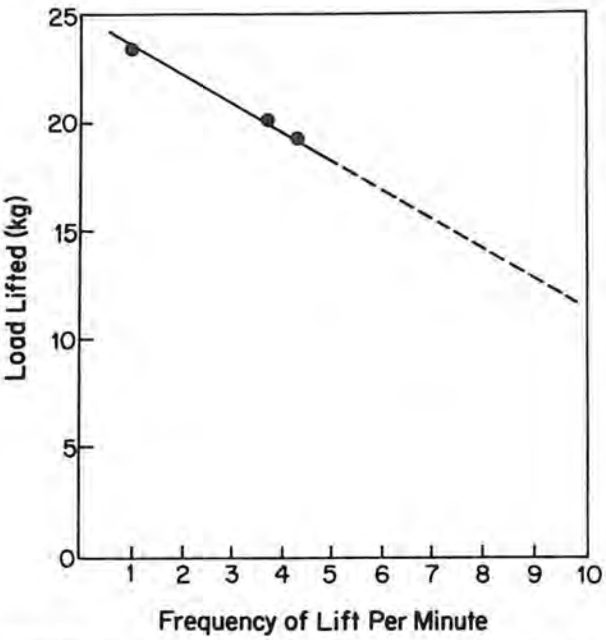

Figure 5. Frequency and weight of lift for floor-to-knuckle height.

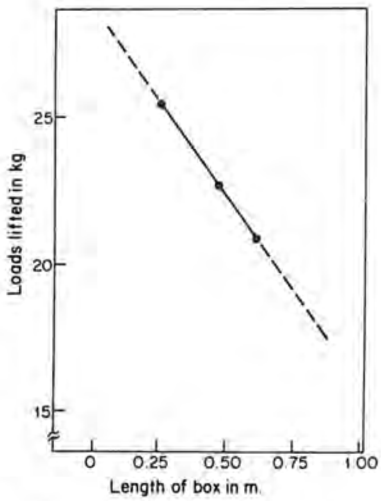

Figure 6. Box size and amount of load lifted.

then,

$$S = \frac{165 \times 170}{1000} = 28.050$$

and
predicted lift = (1.66 × 28.05 + 17.9) .93 = 59.95 lb (27.2 kg)

The model by Aghazadeh was applied to the McDaniel, Dryden, and Knipfer test data to determine the adequacy of this model. Figures 7, 8, and 9 show predicted maximum acceptable weight of lift against the observed maximum acceptable weight of lift for these data. Table 8 shows the predictive

Table 6. Factors for predicting acceptable amount of lift for different heights at different frequencies.

Frequency		C_1	C_2
	Knuckle height		
Frequency of	1	1.87	20.1
	2	1.77	19.1
	3	1.66	17.9
	4	1.57	16.9
	5	1.48	15.9
	6	1.37	14.7
	Shoulder height		
Frequency of	1	2.49	43.6
	2	2.37	33.9
	3	2.22	29.5
	4	2.09	26.7
	5	1.97	24.6
	6	1.82	22.4
	Reach height		
Frequency of	1	1.87	25.1
	2	1.79	26.8
	3	1.68	23.0
	4	1.57	20.6
	5	1.48	18.9
	6	1.37	17.2

Table 7. Factors for box size.

Box length	*Box size factor, C_3*
10	1.00
12	.98
14	.95
16	.93
18	.90
20	.88
22	.86
24	.83
26	.81
28	.78
30	.76

capability of the model at the various frequencies of lift for the three levels of lift. It also shows a comparison of predictive capability of the model when using the McDaniel, Dryden, and Knipfer data. When Tables 5 and 8 are compared, it is clear that the simplified model does not have as good an average error ratio as the individual models reported by McDaniel (1972), Dryden (1973), and Knipfer (1974). However, the simplified model has the following advantages:

1. One model is used for all three levels of lift.
2. One model is used for both males and females.
3. The model does not have sex as a variable.
4. The model requires only two measurements of maximum isometric strengths—back strength and leg strength.

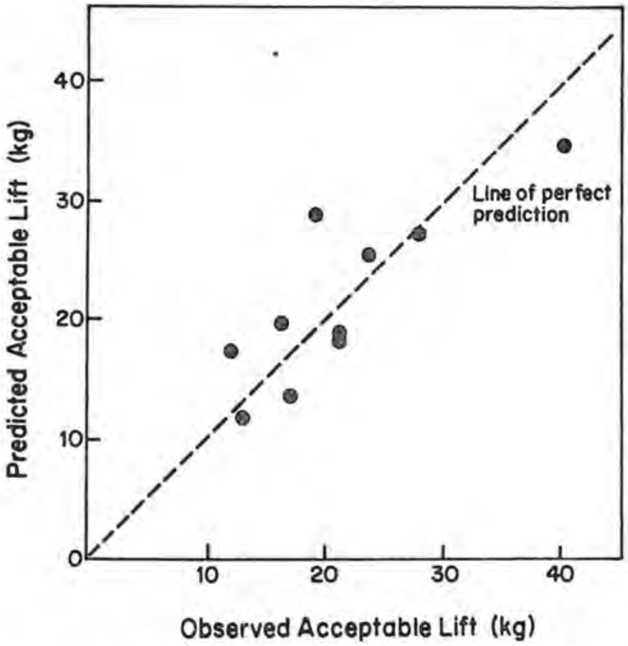

Figure 7. Observed and predicted acceptable amount of lift from floor-to-knuckle height at four lifts/min (McDaniel, 1972).

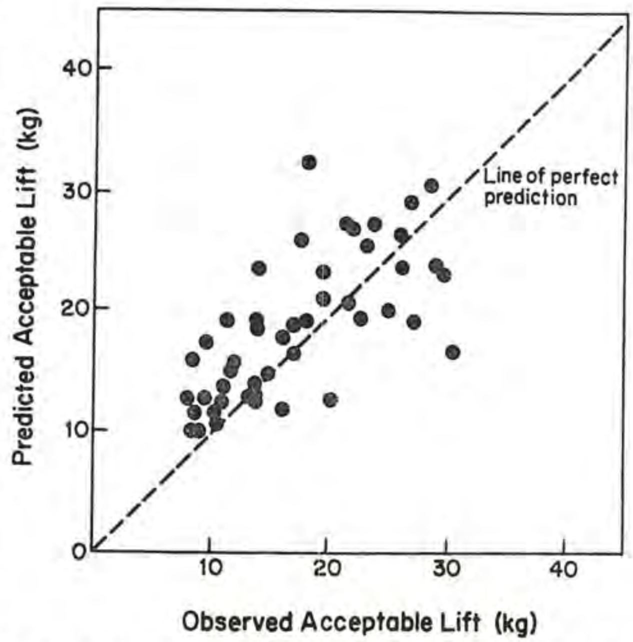

Figure 9. Observed and predicted acceptable amount of lift from shoulder-to-reach height of five lifts/min (Knipfer, 1974).

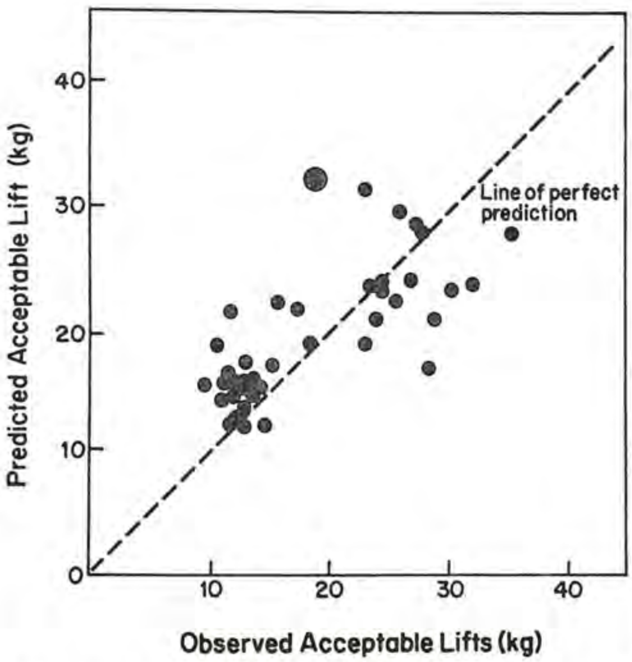

Figure 8. Observed and predicted acceptable amount of lift from knuckle-to-shoulder height at six lifts/min (Dryden, 1973).

Table 8. Predictive capability of models.

Error ratio/ square error	*Data:*	*Frequencies of*			
		2,4 and 6	*2*	*4*	*6*
	McDaniel's	*Knuckle height*			
Average error ratio	.1942	.1344	.1036	.0966	.2364
Average square error	95.94	27.90	30.63	6.86	51.80
Largest error ratio	.5056	.2895	.2121	.2222	.2895
Correlation coefficient	.8206	.9512	.9588	.9866	.7842
	Dryden's	*Shoulder height*			
Average error ratio	.2353	.2678	.4435	.2036	.1814
Average square error	128.77	231.75	503.50	143.57	87.00
Largest error ratio	.8077	.633	.6216	.6333	.5813
Correlation coefficient	.7014	.8356	.9489	.8078	.8124
	Knipfer's	*Reach height*			
Average error ratio	.2442	.1741	.1558	.1813	.1790
Average square error	123.58	90.30	64.40	115.13	80.43
Largest error ratio	.8421	.2957	.1842	.2442	.2857
Correlation coefficient	.6925	.9020	.8563	.9262	.9091

Lifting Capacity

Based on the data from the 125 subjects used with first generation experiments, the lifting capacities for males and females were developed. These capacities are in the form of the lifting distributions for the males and females for each of the lifting ranges based on the average and standard deviation (Table 9). These distributions were assumed to be normal. The male and female maximum acceptable weight of lift distributions can be used as guidelines in the design of tasks. For example, for the male population, tasks requiring lifting of 16.8 kg (37 lb) or less can be performed by 90% of the male industrial work force, in the floor-to-knuckle height lifting range. For the same range, 90% of the female work force can lift 8.6 kg (19 lb) or less. If the tasks are heavier, say, requiring lifting of 29.5 kg (65 lb), then approximately 25% of the male population can perform these tasks and fewer than 5% of the female industrial workers are expected to be able to lift these weights.

Table 9. Summary of lifting capacity of males and females (units are pounds and inches unless otherwise specified).*

Height of lifting task	*Percent of population*				
	90	*75*	*50*	*25*	*10*
Floor-to-knuckle					
McDaniel 1972 (male)†	35	42	53	65	76
McDaniel 1972 (female)†	19	21	33	39	46
Knuckle-to-shoulder					
Dryden 1973 (male)‡	40	47	55	62	69
Dryden 1973 (female)‡	23	25	27	30	31
Shoulder-to-extended-reach					
Knipfer 1974 (male)‡	36	42	49	56	63
Knipfer 1974 (female)‡	18	22	27	31	35

* Based on repeated, continuous lifting tasks. Maximum acceptable lift is sought.

† Students.

‡ Industrial subjects using a 12-× 10-× 9-in. box.

SUMMARY

An ergonomic approach was used in an experiment, which employed male and female workers recruited from industry and male and female students from Texas Tech University, to establish the maximum acceptable weight of lift for three heights of lifting tasks. The results were used to develop predictive models using certain individual characteristics. The models' predictive abilities range between 6.8% to 25.5% for the average error ratio. Current research in this area is considering not only individual characteristics, but also some container and task characteristics in refining these predictive models. Predictive models show a potential for use in screening methodologies to achieve proper placement of workers on jobs requiring lifting tasks.

The results show that the maximum acceptable weights of lift for females were lower than those lifted by the males. The female's maximum acceptable weights of lift range between 49% to 62% of the maximum acceptable weight of lift for the males.

The discrepancies evident from the three investigators' data (Table 9) may result from variation in the methods used, or variation in the subjects (in terms of age, sex, size, and national origin), or both.

Lifting capacities similar to those shown in Table 9 can, however, serve as a guide for designing new jobs or modifying existing jobs to accommodate a larger percent of the workers.

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RISK-TAKING IN MANUAL MATERIALS HANDLING

J. E. Shealy

INTRODUCTION

The industrial losses as a result of manual material handling have been well documented. Research on the biomechanics of lifting, the efficiency of workplace design, maximum lift (both weight and height), and work-rest cycles are but a few of the areas that have been considered. The effects of physical condition, age, and gender are among the factors that have been extensively reviewed and reported (Brown, 1972). The efforts of safety engineers to reduce hazards within the environments in which people play, work, and live have reduced accidents by most measures (Haddon et al., 1964). One area that has received relatively little attention is the factor of risk-taking in manual material handling.

Risk-taking in general has been the subject of a great deal of research since the early 1960's. Although it has been a fertile area for research, the results have been rather meager. The efforts of psychologists and others to identify a general personality trait known as risk-taking (RT) has not been very successful. The failure to find a strong trait that is general to all modes of behavior has not caused people to cease looking for the trait. Although RT is an intuitively appealing cause with reams of anecdotal evidence to support it, there is precious little empirical evidence to indicate that RT, in the real world, is the strong trait described above. A recent publication from the British National Institute of Industrial Psychology (Hale and Hale, 1972) offers a rather gloomy review of psychologically oriented research in industrial situations. This publication analyzes the many methodological, statistical, and logical flaws of much of the literature in this area.

RT DEFINITION

Let us define risk for the purpose of this paper to be the exposure to hazard or danger with the concommitant possibility of loss or injury. RT in this context then becomes that behavior involving a choice or decision in a situation with overt perception of risk where the choice differentially affects the subjectively perceived outcome probabilities. It is important at this point to distinguish between "overt perception" or çonscious behavior and other possible types of RT. In the context of a useful definition, RT should imply a degree of knowledge rather than ignorance. If a person were to subject himself to a great danger but was unaware of the danger (such as a person unwittingly walking past a building as a safe falls out of a window on an upper floor), the act of placing himself in the position could be considered risk-taking but would hardly fit the notion of "informed consent" that is implied when a person deliberately inserts his hand in a piece of moving machinery where the hand might be injured. This is frequently a difficult parameter to assess, as it is not a binary or discreet variable, but one that exists in degrees.

The question of subjective versus objective risk must be considered when skill is a factor. Subjective risk is defined as the risk level perceived by the individual. The objective risk is the risk level expressed in terms of the overall population probability of failure. Translated into a hypothetical example, consider the situation of driving an automobile. For the average motorist to venture on a rainy highway at speeds of 100 mph could be a very risky endeavor, at least in part because of their lack of skill; for a professional race driver, however, the same situation would present less risk (subjective perception thereof) because of greater skill and experience. The same might hold with regard to other more industrially related tasks such as manual materials handling.

Ultimately, if one believes that RT is a viable concept, the urge to apply it in a constructive manner will appear. The problem then becomes one of quantification and measurement. A great deal of effort has been spent on this aspect of RT, which is covered in the next section, below.

THEORIES OF RISK-TAKING AND RELATED STUDIES

Before the theoretical constructs of RT behavior can be reviewed, the assumptions about RT must be considered. In its most simple approach, personality theorists assume that personality characteristics are stable, pure, enduring traits that are general to all phases of an individual's behavior. RT has proven an elusive target under those assumptions.

Since the object of interest is individual performance on risky, skilled tasks, this review is limited, in the main, to studies in that area.

The research literature on RT has been summarized by Slovic (1964), Kogan and Wallach (1967), and Pruitt (1971). The literature generally deals with RT behavior in broad terms, with a lack of agreement as to what constitutes RT. Little attention has been paid to the relationship between RT and trauma-producing accidents. The tests available to measure RT lack strong convergent validity (Slovic, 1962; Weinstein, 1969). Studies generally do not distinguish clearly between chance and skill dominated events, even though this important dimension has been recognized for some time (Kogan and Wallach, 1964; Rotter, 1966; Kogan and Wallach, 1967).

The effect of the length of time for making a decision under risk (Dearnaley, 1958; Streufert and Streufert, 1968) has been studied. In general, the findings have been that as time for a decision decreases, the choice tends to be more conservative; whereas, if the decision is delayed, i.e., the person has more time to ponder his decision, the level of RT increases.

The work done on RT as a function of age is not extensive. Kass (1964) looked at the difference between the years 6 to 10, which is not a large enough span to help understand adult behavior. Kogan and Wallach (1960), however, did look at the difference between college students and their intellectual equivalents at a mean age of 70. They found that the older subjects, both male and female, were more conservative than were the college subjects. In a similar study, Botwinick (1969) found that in elderly versus young adults, that the elderly chose nonrisky situations, thereby avoiding the need to choose between levels of RT in the risky situation, regardless of the probability of success. From this, he concluded that the main effect of age was to avoid risk rather than to increase the caution in decision making. In both the Kogan and Wallach as well as the Botwinick findings, we do not know if the observed differences are developmental or cohort/environmental in nature.

In a section on "Attitudes and Motivation" (pp. 54-59), Hale and Hale (1972) cite four of the better studies (commissioned by the European Coal and Steel Community) that looked at attitude to risk and its relationship to safety. From the studies, it was concluded (Merz (1967) and Rockwell (1967), cited in Hale and Hale (1972)) that the accident repeater, when compared with the control group, tended to adopt more dangerous strategies and faster speeds. Knowledge of accidents to themselves and fellow workers failed to alter the strategy of the accident group. It appears that accident repeaters accepted higher levels of risk and learned less from their mistakes than accident-free people.

Strub (1969) found that the more experienced the person was, the higher the level of objective risk accepted. Jellison and Riskind (1970) found that RT behavior and ability are positively related. As a person becomes more experienced and skilled, the subjective evaluation of the risk inherent in the situation goes down because the person has more ability to perform the task and, thus, has raised his objective probability of success. This points out the importance of distinguishing between objective and subjective RT. Lupfer and Jones (1971) found that RT under skill conditions led to a higher mean level of objective RT, and less variance, than under chance conditions. This probably reflects the belief that because the task is skill- rather than chance-dominated, the individual has more control over the outcome and, thus, will accept higher objective levels of RT. This is consistent with a maximizing strategy. The decreased variance is indicative of greater certainty in choice behavior. As noted earlier, the definition of RT behavior must consider skill as a factor.

There are many different situations in which one may experience RT behavior. There are many different kinds of risk (task success, physical trauma, monetary, social or peer group approval, ego, etc.) and many variables potentially affecting one's behavior. Slovic (1964); Lillibridge and Lundstedt (1967); and Cartwright (1971) have pointed out that many previous studies adopt too simplistic a view of the complexity of RT behavior. The current literature makes it abundantly clear that RT behavior is multidimensional in nature. In contrast, many studies in the past have acted as if it were unidimensional. Many studies have ignored the situational aspects of the behavior. There seems little doubt but that RT behavior is situation specific in many aspects (Slovic, 1964 and 1971; Shealy, 1973; Raynor, personal communication). If true, this suggests that standard forms that do not consider the situation will rarely account for very much variance.

In a now classic piece of work by Cohen, Dearnaley and Hansel (1956), the degrees of hazard, degrees of risk, and level of risk taken were found not to be linearly rated. Cohen (1960) makes the point that what people estimate they can do, what they will actually attempt, and finally what they can accomplish are not necessarily coincident. It is this mismatch between estimates and accomplishments that is interesting. In a driving task, Cohen et al. (1956) found that when the task was easy (i.e., low risk) the tendency was to underestimate one's abilities (be conservative). As the task became more difficult, the tendency was to overestimate one's ability (behavior became more risky). From this research, several conclusions are possible. First, people will attempt tasks where one is not certain of success (i.e., man is a risk-taker). Second, man tends to be poor at estimating the probability of success when the task is either relatively safe or relatively hazardous. It is as if hazard existed on a log scale, but our estimation was on an arithmetic interval scale, where the middle part of each scale is in approximate congruence.

One's attitude toward risk is subject to modification. In Cohen et al. (1956), they found that by training, the risk judgment could be altered so that the trained driver would not attempt as risky a level of performance as the untrained driver. In other words, training had the effect of a shift in criterion towards more conservative choices of behavior, but not necessarily more skillful judgments. In a subsequent study (Cohen et al., 1958), it was found that alcohol had the opposite effect on judgment, i.e., less conservative judgments, but no improvement in skill.

The cultural effect on RT cannot be ignored. Suchman (1965) points out that RT is rewarded in many ways in our western society. Awards and medals are given to heroes who risk their lives in hazardous feats. We admire those who dare to attempt difficult tasks. Huberman (1969) found that risk, as a characteristic of the situation, has motivational attributes. One should not overlook the effect of machismo or showing off that will result from peer group pressure and ego involvement. This could very well be the difference between a person attempting or not attempting to lift something that was too heavy for him. Brown (1965) points out that the appearance of attempting difficult tasks, i.e., risky tasks, will often elicit peer approval and admiration.

At the risk of violating the principle laid out above, that of avoiding too simplistic a model of RT, some theoretical constructs of RT will now be discussed.

Factors that seem to have found support in various studies are extroversion, need for achievement, and locus of control.

Extroversion

Of the many personality inventories commonly used, one of the more popular is the Minnesota Multi-Phasic Personality Inventory (MMPPI). Fine (1963) used the MMPPI to test Eysenck's (1962) theory of extroversion. He found that drivers that had bad driving records tended to be diagnosed as extroverts whereas those with good driving records were scored as introverts.

In an extension of Eysenck's theory, Welford (1966) hypothesized that personality is a function of the mean brain electrical activity levels. Welford found that the mean level for extroverts was lower than that of introverts. From this he further hypothesized that extroverts needed external stimulation to remain aroused and therefore would become rapidly bored with monotonous, repetitive tasks, whereas introverts would avoid external stress that could push their arousal level too high. A logical extension of these hypotheses would predict different accident involvement as a function of the situation and personality type. This hypothesis was in fact confirmed by McBain (1961). Alternatively, in Surry's book, *Industrial Accident Research* (1974), he quotes a psychologist (Professor P. Foley) as saying that he had not found support for Eysenck's theory of two types of people (extroverts and introverts). A common criticism of the extrovert theory of RT is that extroverts tend to talk a lot and therefore the higher rate of accident/injury involvement might be a consequence of a reporting artifact rather than a true theory (Powell et al., 1971).

Need for Achievement

The area of need for achievement (n Ach) and RT was first explored by Atkinson (1957). This was an outgrowth from his earlier work (McClelland, Atkinson, Clark, and Lowell, 1953) on the theory of achievement motivation. In these studies, the content of imaginative stories generated by subjects with thematic apperception test (T.A.T.) type stimulus material are analyzed for evidence of achievement orientation. Atkinson and Feather (1966) refined the theory of achievement motivation. Basically, he and others (Atkinson et al., 1960; McClelland, 1961; Brody, 1963; Smith, 1963; Locke, 1965; Meyers, 1965; Morris, 1966; and Raynor and Smith, 1966) have found that people with a high n Ach generally pick moderate levels of RT, whereas those with a low n Ach choose either high or low levels. This general finding has been found to be valid over a large range of risk behavior situations; on the other hand, it has not been found to be a very good predictor. The research results are fairly consistent and are usually better in skill- rather than chance-dominated events. The main problem with n Ach studies is that when a subject

(S) is low in n Ach the RT direction cannot be predicted; one can only predict that the S will choose a high or low level of RT as opposed to a moderate level.

Kogan and Wallach (1967) are strongly critical of the n Ach studies in that they have: (1) generally not controlled for the differential effects of individual skill levels, and (2) generally relied on laboratory studies where the task has been rather trivial and the rewards and risks may have failed to truly engage the subject's RT disposition. However, they do agree about the overall consistency and success of the n Ach studies, and the objection regarding the lack of control for skill level is partially mitigated by the use of a subjective definition of RT as the basic theoretical construct. However, the general thrust of the n Ach studies has been limited by their focus on task success and failure considerations of RT; the subject has not been faced with the risk of physical danger (trauma).

According to recent work by Raynor (1974), the n Ach measure may be more sensitive to long-term goals, such as career or life-long aspirations, rather than to short-term goals. Within this context, Raynor finds that the high need achiever tends to be very conservative at the micro level as he views each situation as a hurdle that must be cleared before attempting the next in a succession.

Using the model of Raynor, one would predict that people who are high in need for achievement would tend to be low in RT on short-term goal oriented tasks if they perceived that short-term goal as being important to their future long-term aspirations. "Important" could be interpreted here as meaning that success on the task was essential for future goal achievement or that, if the success was not particularly important, failure might preclude future long-term goal achievement. (For example, competing in sports might not be important in itself, but if failure in the activity meant a broken leg, it might then preclude participation in other activity that is long-term goal oriented, such as school.) This interpretation probably goes beyond the aspiration levels of a typical person engaged in manual materials handling. One could therefore predict that low levels of n Ach might result in high levels of RT for some people.

Locus of Control

Another theoretical construct frequently mentioned in this context is the locus of control (LC). The underlying assumption is that some people possess an internal LC (ILC); they perceive that they have control over what happens to them (the individual is an active, causal agent), whereas others possess an external LC (ELC) and believe that what happens to them is a matter of "fate" or the gods (a passive recipient of environmental effects). Several instruments have been devised to evaluate and measure LC. One of the most popular is the Internal-External (I-E) Scale devised by Rotter (Rotter and Rafferty, 1950; Rotter, Liverant, and Seeman, 1962; Rotter, 1966). The instrument comes in two versions; open ended and forced choice. In the open ended version, S's are instructed to complete a sentence in such a way that it expresses their real feelings. In the forced choice version, two options are worded to reflect either an external or internal LC. In the open ended version, the replies must be interpreted in an I-E framework.

The LC findings (Liverant and Scodel, 1960; Rim, 1965; Baron, 1968; Higbee and Streufert, 1969; Cummings and Mize, 1969; Van der Bergh, 1969; Throop and MacDonald, 1971; and Sims and Bauman, 1972) are consistent: the more external the LC, the higher the level of subjective RT, and the more internal the LC, the less RT.

The finding that an ILC is associated with low RT appears contrary to the finding that as skill, ability, and experience increase, so does RT. It seems reasonable that as skill is acquired, the person's feeling of control over events would increase, corresponding to a shift towards greater ILC. This apparent contradiction is the result of confusion between subjective and objective RT. The same term (RT) is used to describe two different things. In the case of skill, ability, and experience findings, RT is generally described as the population-wide objective probability of success without regard to the increase in the individual perception of success that comes with increasing skill, ability, and experience—a rather serious methodological flaw as pointed out by Kogan and Wallach (1967). In the case of the LC studies, the RT is at an individual subjective level. The crucial point is that a beginner and an expert do not have the same objective probability of success on a given task nor do they have the same capability for escaping trauma for a particular level of attempted performance. It, therefore, follows that if they have the same subjective perception of risk and, for example, will only attempt a task where they think they have a .5 probability of success, they will pick tasks at two very different levels of risk from a population-wide objective probability of success.

The LC instruments have been criticized by Raynor (1973, personal communication) as being too universal in scope. Raynor suggests that for the LC scale to be useful, it should contain situation-specific detail that would orient the S to the context of the RT situation. This is essentially what Sims and Bauman (1972) did in their study of tornado coping styles. Van der Bergh (1969) likewise spoke of operating styles within the context of vehicle driving as opposed to a more general trait.

By going to a situation-specific instrument, Sims and Bauman (1972) as well as Van der Bergh (1969) obtained possibly stronger findings than if they had used only the standard instruments. Shealy (1973) on the other hand used both instruments in a study of RT in skilled task activity. He found that the general instrument did not discriminate between accident and nonaccident subjects, whereas a situation-specific instrument modeled after the forced choice LC test did successfully discriminate between the two groups.

The study by Sims and Bauman (1972) used a situation-specific instrument in the style of the Rotter Locus of Control open ended version. They examined the coping style of two groups of people to the threat of tornadoes. In this case, the exposure to risk was not equal. A group of people from Illinois were compared with a matched sample from Alabama. The Illinoians were exposed to a more severe threat (more tornadoes per season and of greater average intensity) than were the people from Alabama. In spite of a greater exposure to risk, the northern group had a lower death and injury rate both on a per capita and per square mile basis. Obvious factors such as population density, quality of buildings and shelter structures, etc., did not explain the findings. It was suggested that perhaps the LC orientation of the two groups was related to their death and injury rates. The analysis of the responses of the two groups showed that the northern group expressed a significantly greater internal LC than did the southerners. This LC orientation was manifested in each group's coping style. The northern group typically sought protection, listened to the radio, and heeded tornado warnings (displayed internal control over their lives) whereas the southerners believed that what happened to them was a matter of luck or fate (left the outcome to external forces).

Because of time constraints, Sims (personal communication) was unable to give both the standard LC and his situation-specific LC tests to his subjects. Sims stated, however, that he believes the standard LC is measuring a broad and general personality trait that is rather weak and tends to be strongly influenced by situation-specificity. Sims states that although he did not test for correlation between his specific test and the standard LC, he would not be surprised to find a moderate positive correlation. He also believed that, everything else being equal, the standard LC should predict but that it would probably take a relatively large sample because of the weakness of the general trait.

Van der Bergh (1969) found essentially the same thing with auto accident victims. He found that accident-prone drivers were characterized by a laissez-faire attitude, took unwarranted chances, and failed to learn from close calls when compared with the control group. They left things to chance and commonly acted in what could be characterized as an ELC frame of mind; whereas the accident-free group did learn from close calls and acted as if they believed that what they did would directly influence what was going to happen to them. This generally describes the ILC orientation.

Shealy (1973) found that the general LC test was not able to significantly differentiate between accident-involved individuals and the population at risk in a longitudinal, closed population, epidemiological study of Alpine skiing injuries. At the same time, however, a situation-specific LC type instrument was able to significantly ($\alpha=0.05$) differentiate the accident group form the population.

A major question raised by the preceding review is whether the n Ach and LC studies are looking at two different aspects of RT. As previously stated, n Ach is concerned with task success and failure considerations; its relationship to trauma is not clear. Although LC constructs are not confined to RT with regard to trauma, these LC studies are primarily concerned about the use of abilities to avoid danger or trauma. The more internally oriented individual takes rational, objective measures to limit damage. The externally oriented person assumes that external forces either will or will not protect him from the environment.

In summary, the literature relevant to skilled individual performance indicates:

1. Accident repeaters apparently fail to profit from their mistakes, and work at higher levels of risk (in terms of operating strategies) than do control groups.

2. People with higher ability seem to take more risks, but this is probably an artifact of the failing to control for the true differential danger to the individual as a result of different skill levels.

3. People with high n Ach take moderate risks, people with low n Ach take high or low risks, within the context of task success or failure.

4. People with ILC behave in ways that minimize actual probability of trauma compared to people with ELC, i.e., accept low levels of risk of physical danger of trauma.

5. Risk has motivational qualities (can be a means to an end) leading to direct satisfaction and/or satisfaction from the social environment.

6. Extroversion has many of the same characteristics as locus of control, in that extroverts and external locus of control oriented people tend to act in much the same way.

7. Situation-specificity must be included as an important factor when attempting to measure RT and make predictions.

IMPLICATIONS FOR INDUSTRY AND RESEARCH

Implications and generalizations from the foregoing must be made with great caution. None of the reviewed research dealt specifically with manual materials handling. Most of the research was not done in the real world. In the few situations where the real world has been carefully observed, it was quite clear that whatever role personality might have, it would be relatively small and insignificant relative to the hazards of the workplace itself. Powell et al. (1971) found that three factors were of over-riding influence:

1. that risks were so much an integral part of work systems as presently arranged, that the more work was done, the more accidents occurred;

2. that the risks accompanying each task were specific and could be changed by changing details of the task; and

3. that people reduced their accident rate by gaining experience, i.e., they learned to avoid risks. But this experience was also highly specific and became blurred after time spent on other tasks.

Consequently, one could say that only if the above factors had been properly attended to, then one might want to take a look at RT, as an accident related variable. From the reviewed literature, it appears that there is a measurable trait called RT. This trait is not constant; it shifts with age and with the specific situation. It can be altered; it can be measured. This suggests, then, the three classic approaches of:

- selection,
- training, and
- job design.

For selection, RT could presumably be tested. Be advised, however, that the weapon is a rather weak shotgun. The instruments available are not very strong or very specific. To use RT as a selection tool, a measurement test (like the n Ach or LC tests) would need to be devised and made specific to the task of manual materials handling.

In the case of training, the literature suggests that the training results in a shift of criterion (vis-a-vis Signal Detection Theory) rather than in increased sensitivity or judgment power (d'). The implication, then, for manual materials handling is that the training must include information related to the decision-making process. The judgment of personnel evidently cannot be improved with regard to what is possible (i.e., more exact knowledge of capacity); rather, the training will cause the person to be more cautious in trying to lift or move something.

Job design probably offers the greatest opportunity. It is rather clear that part of the RT dilemma is decision-making under conditions of uncertainty. Therefore, anything that a designer could do to bring about a reduction in uncertainty would probably reduce the objective risk in the situation and would thus aid the decision-maker in making the correct judgment. This might involve better labeling of weights and centers of gravity; it might include putting handholds on packages and other objects that must be moved by hand. In other words, job design must take into account the personality characteristics of the population.

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OPTIMUM DESIGN OF CONTAINERS FOR MANUAL MATERIAL HANDLING TASKS

M. A. Ayoub

INTRODUCTION

Containers (the objects to be handled: lifted, pushed, pulled, etc.) can be characterized in terms of the following:

- weight of the container and its contents;
- distribution of the weight inside the container (e.g., uniform density versus uneven distribution of the load within the container);
- geometry (shape and bulk) of the container;
- stiffness of the load and/or of the container itself; and
- possible modes of interface between the container and the man performing the task. (This interface can be facilitated thru the use of handles and similar coupling devices.)

Herrin et al. (1974) give a detailed review of the literature on container characteristics as related to manual materials handling. Several design problems associated with containers typically used in manual tasks are presented and discussed with the use of several examples in the following section.

EXAMPLES

Example 1

In the manufacturing area of a large textile plant, operators are required to lift and transport product units weighing either 5.0 or 6.4 kg (11 or 14 lb). The manufacturing area contains machines for producing the products, a conveyor system for transporting the products to other areas in the plant, and carts that are used for storage of tools and as a place for in-process inventory of the product. Operators work under a noise level of 103 to 110 dBA for 450 min per work shift. This requires all operators to wear ear plugs. Levels of illumination, temperature, and humidity are controlled and meet existing safety and health standards. Fumes are occasionally noticed in the manufacturing area, but there are no airborne particles present. The floor is concrete and has no "fatigue reducing" mats because buggies and carts must be rolled through the area. Almost all operators are males in good health with an average age of 23 yr. Each operator works between the machines and the outgoing product conveyor (Figure 1). The cart is usually placed to the operator's left as he faces the machines. Approximately 16 steps and 16 body turns occur during each work cycle (loading and unloading the products). The product is removed from the machine at two different heights and then is placed on the top surface of the cart. A tool is used to remove two product units from the machine at a time (Figure 2). The product units are lifted slightly to a support on the cart for checking and are then lowered and transported to the conveyor. The geometry of the workplace makes it possible for operators to use proper lifting and lowering techniques. As a general rule, however, operators have the tendency to twist the body rather than turn with the feet. Total cycle time per machine (multiple machines are served by each operator) is 8 min. Operators remain standing for the larger part of the work shift, i.e., they sit only during rest periods.

The workplace, as presented above, depicts many obvious handling problems that warrant further analysis and assessment; however, discussion will be limited to the design of the product-removal tool—the container in this case.

As shown in Figure 2, in handling the tool, the operator performs two functions: provides a reactive torque at point a, and balances the tool and the product units over point b—the right hand. The torque and the resultant reactive force can be computed by considering the equilibrium of the tool-load aggregate.

Let

F_1 = force applied by the left hand at point a, and

F_2 = force maintained by the right hand at point b.

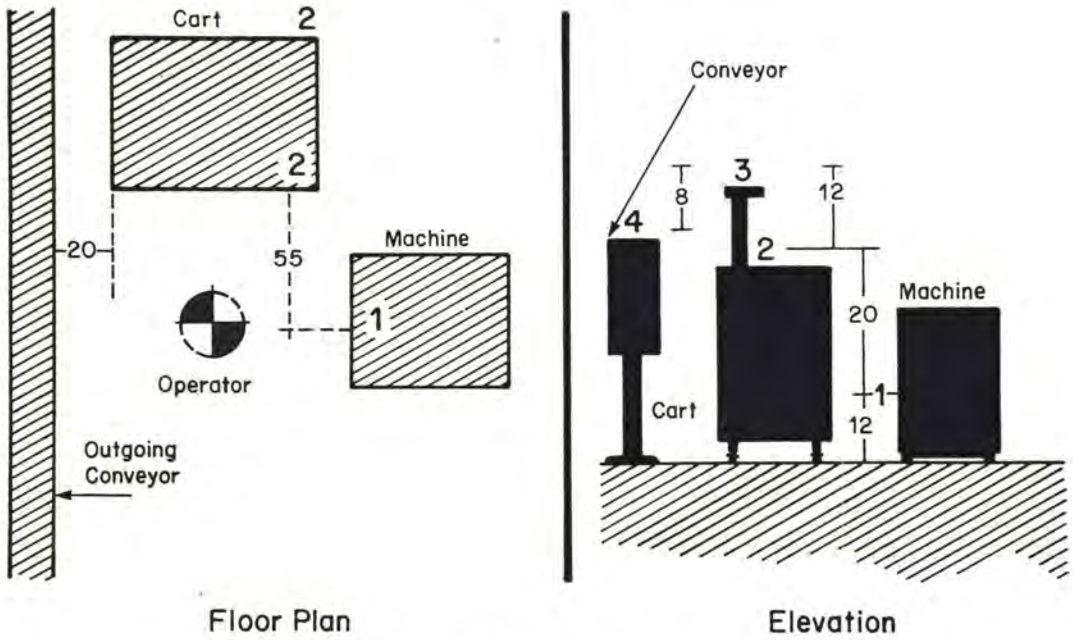


Figure 1. Workplace layout (imperial units, inches).

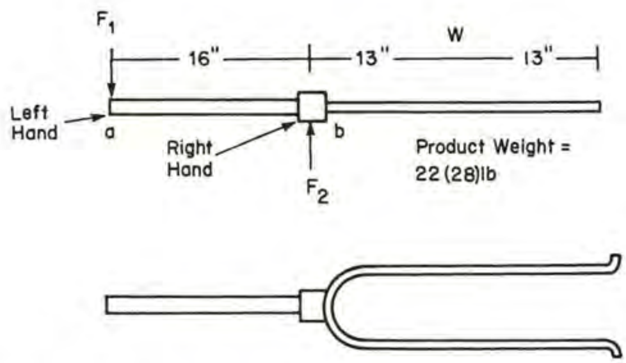


Figure 2. Product removal tool, current design.

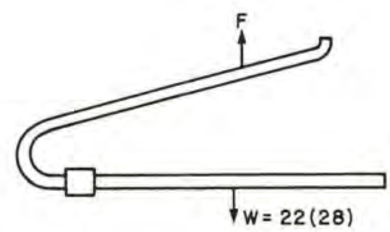


Figure 3. Product removal tool, proposed design.

For equilibrium, we write (see Figure 2)

$$F_1 \cong 8.2 \text{ to } 10.5 \text{ kg } (18 \text{ to } 23 \text{ lb}) \quad (1)$$

$$F_2 \cong 20.5 \text{ to } 23.6 \text{ kg } (45 \text{ to } 52 \text{ lb}) \quad (2)$$

From Equations 1 and 2, it is clear that because of the current tool design, the operator is required to apply a substantially larger force (perhaps twice as much) than is actually necessary. The operator's effort in handling the tool with the product units can be reduced significantly if a design similar to the one shown in Figure 3 is adopted. The new design brings the weight and the reactive force (muscular effort) together in such a way that their lines of action coincide; thus, the net force required for performing the task is kept to just the magnitude of the external load, 12.7 kg (28 lb).

This example shows how the use of simple mechanics (see Figure 4) can be used effectively to design and evaluate lifting tasks, especially the design of containers.

Example 2

A biomechanical reference load for manual lifting tasks can be defined as one that induces a torque T at the L_5/S_1 spinal joint. The load is assumed to be highly concentrated, and, as such, its size—for all practical purposes—can be assumed to be negligible. The distance between the load and the L_5/S_1 disc is L. If the resultant lifting torque is to be kept constant (i.e., equal to T), what is the maximum weight that can be placed in a container of size s?

a)

$$F_1 = W\left[1 - \frac{2s}{4s^2 + \ell^2}\right]$$

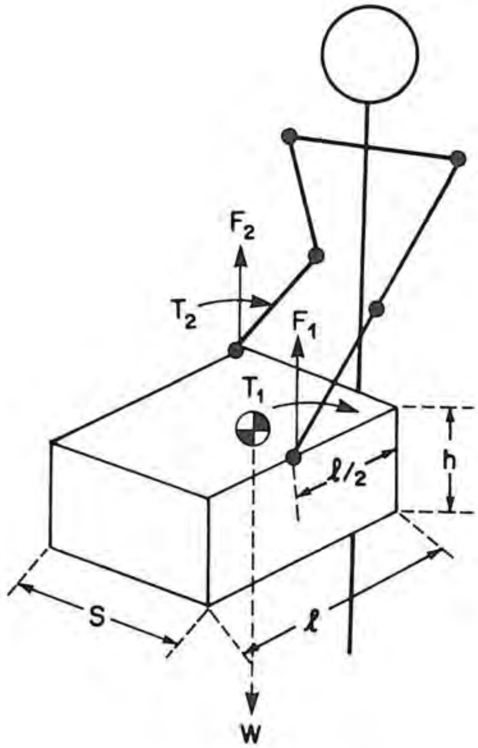
$$F_2 = W\left[\frac{2s}{4s^2 + \ell^2}\right]$$

$$T_1 = WX\left[1 - \frac{s}{2s^2 + 0.5\ell^2}\right]$$

$$T^2 = WX\left[\frac{s}{2s^2 + 0.5\ell^2}\right]$$

where

$$X = \left[\frac{s^4 + 0.25s^2 l^2 - s^2}{4s^2 + l^2}\right]^{1/2}$$



b)

$$F_1 = \frac{2\ell^2 - s^2}{12\ell^2 + 3s^2}\left[3W_1 = W^2\right]$$

$$F_2 = \frac{6W_1\left[s^2 + \ell^2\right] + 2W_2\left[5\ell^2 + 2s^2\right]}{12\ell^2 + 3s^2}$$

$$T_1 = \frac{3W_1X\left[6\ell^2 - 3s^2\right] + W_2X\left[2\ell^2 - s^2\right]}{36\ell^2 + 9s^2}$$

$$T_2 = \frac{18W_1X\left[s^2 + \ell^2\right] + 2W_2X\left[5\ell^2 + 2s^2\right]}{36\ell^2 + 9s^2}$$

where

$$X = (\ell^2/16 + s^2/4 - (s^2 + \ell^2)^2/(4\ell^2 + s^2)^{1/2}$$

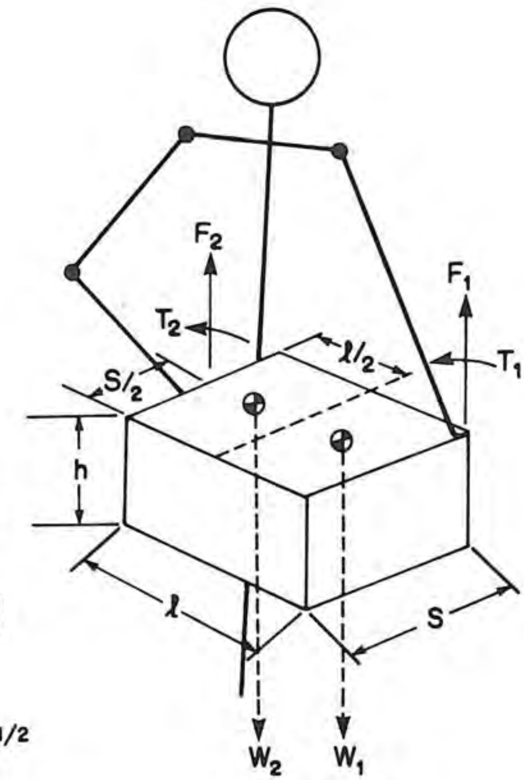


Figure 4. Reactive forces and torques as a function of mode of holding and dimensions of container (upper, Case a; lower, Case b).

The question posed above is one that has received considerable attention (directly or indirectly) from many researchers in the field (e.g., McConville and Hertzberg, 1966; Tichauer, 1971). There is a general consensus in the literature that as container size (its dimension in the sagittal plane) increases, the permissible weight to be handled should decrease proportionately.

This relationship between the load and its size can be derived as follows:

Let

W = weight of the reference load, and

L = distance between the load (center of mass and point of holding) and L_5/S_1 disc.

The reference torque is given by

$$T = W \times L$$

Now, consider the container of size s. We define $\overline{W}$ as the maximum weight to be placed in the container. For maintaining constant torque, T, the following condition should be satisfied:

$$W \times L = \overline{W}\,[L + s/2] \qquad (3)$$

The hands are assumed to be at a distance L + s/2 from L_5/S_1 disc. From Equation 3, it follows that

$$W = W\,[\frac{L}{L + s/2}] \qquad (4)$$

Equation 4 depicts a linear relationship between the load and its size. This relationship is in agreement with the lifting literature; e.g., see Figure 5. Equation 4 can be modified to account for the effects of having handles (coupling devices) placed on the container.

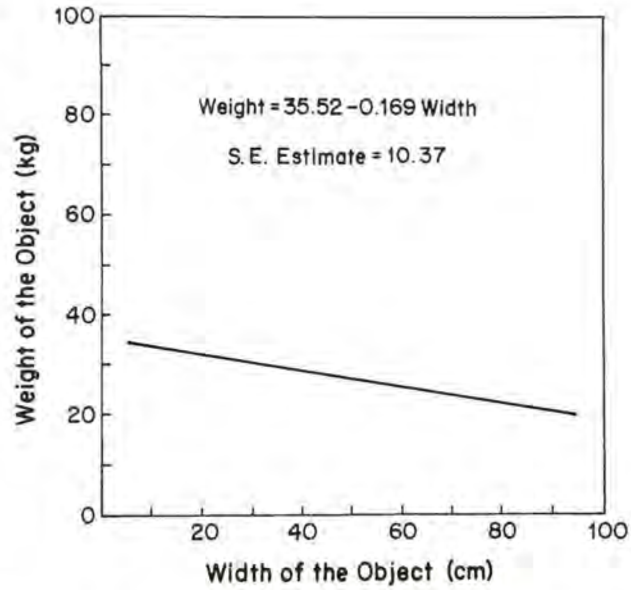


Figure 5. Lifting capacity as a function of container size (based on data from McConville and Hertzberg, 1966).

Example 3

A computer manufacturing firm packages small electronic components in cardboard containers that measure s × h × *l*. Based on an economic study of several modes of transportation, W is selected as an acceptable minimum weight for each container. The delicate nature of the electronic components necessitates that all handling be performed manually. What are the optimum dimensions for the containers? Assume a uniform average density of ρ for the components.

Lifting literature supports the premise that the bulk and weight of containers are the primary contributors to the total torque induced at the L_5/S_1 disc — the critical joint of the spine. As is always the case, the weight of the object (and consequently the container) is fixed. In this case, the designer is left with the task of defining an optimal shape for the container. It is proposed here to accomplish this by formulating the problem as a nonlinear optimization model, then proceeding to solve it by using the Lagrange multiplier technique. For the model, the obvious objective function would be one that is written in terms of the bulk (or surface area) of the container. Minimizing this function, subject to the minimum weight constraint, would yield an optimum design for the container.

Mathematically, the optimization model can be stated as follows:

Minimize:

$$Z = s \times h + s \times l + h \times l \qquad (5)$$

Subject to:

$$s \times h \times l \times \rho = W \qquad (6)$$

Using the Lagrange multiplier technique, we write

$$L = s \times h + s \times l + h \times l + \lambda\,[s \times h \times l - \frac{W}{\rho}]$$

By differentiating L with respect to s, *l*, h, and λ, and then proceeding by setting the derivatives equal to zero, we obtain

$$\frac{\delta L}{\delta s} = h + l + h \times l = 0$$

$$\frac{\delta L}{\delta h} = s + l + s \times l = 0$$

$$\frac{\delta L}{\delta l} = s + h + s \times h = 0$$

$$\frac{\delta L}{\delta \lambda} = s \times h \times l - \frac{W}{\rho} = 0$$

Solving the above simultaneous equations, we find the optimal dimensions for the container.

$$s^* = h^* = l^* = (\frac{W}{\rho})^{1/3}$$

and

$$\lambda = -2/W^{1/3}$$

The model objective function attaches equal weights to all the container dimensions (s, h, and l). However, an increase in s would have a pronounced effect on the torque produced at L_5/S_1, more so than any comparable increase in l or h. To account for this, the objective functions should be changed to read

$$Z = P_1 \times s \times l + P_2 \times s \times h + P_3 \times h \times l$$

where

P_1, P_2, and P_3 = relative costs (penalty) associated with per unit area increase in the container panels.

To illustrate the effects of including these differential costs on the optimum solution, the model was solved once more with $P_1 = 3$, $P_2 = 2$, and $P_3 = 1$. This resulted in the following optimum solution

$$s^* = 0.5(\frac{W}{\rho})^{1/3}$$

$$l^* = 1.1(\frac{W}{\rho})^{1/3}$$

$$h^* = 1.8(\frac{W}{\rho})^{1/3}$$

The use of the Lagrange multiplier technique was not a prerequisite for solving the simple model of this example. Indeed, the same answer could have been obtained if the model was solved by the use of differential calculus directly after utilizing the constraint equation to eliminate one of the variables in the objective function. On the other hand, techniques of nonlinear programming should be used for solving the model if problem formulation or conditions call for the use of inequality constraints (for an introduction to these techniques and similar ones, see Wilde and Beightler, 1967).

Example 4

A machine part consists of two components that weigh W_1 and W_2 lb, respectively. The possible weights for each part can vary from 10 to 60 lb (4.5 to 27.3 kg). Because of engineering and production requirements, the minimum acceptable linear dimensions for the two parts are 20 and 10 in. (510 and 255 mm), respectively. A container is to be designed for shipping the machine part as well as other similar ones. (See Figures 6 and 7 for the container loading diagram.) The part components can be shipped together or separately. All the containers will be shipped to plants where most of the handling tasks are performed manually. If it is desired to limit the handling effort to approximately 30 lb (13.6 kg) per hand (reactive force), what is the optimum weight for each container?

The problem here is to determine the maximum possible values for W_1 and W_2 while maintaining the resultant hand force less than or equal to 60 lb

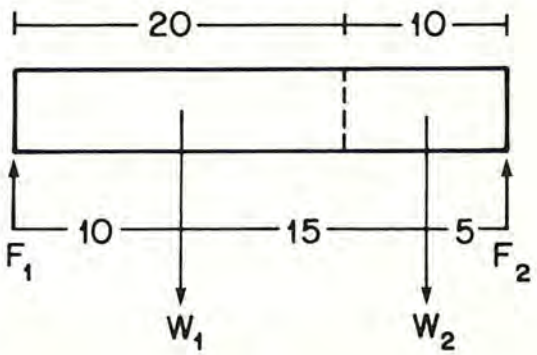


Figure 6. Loading diagram for the container.

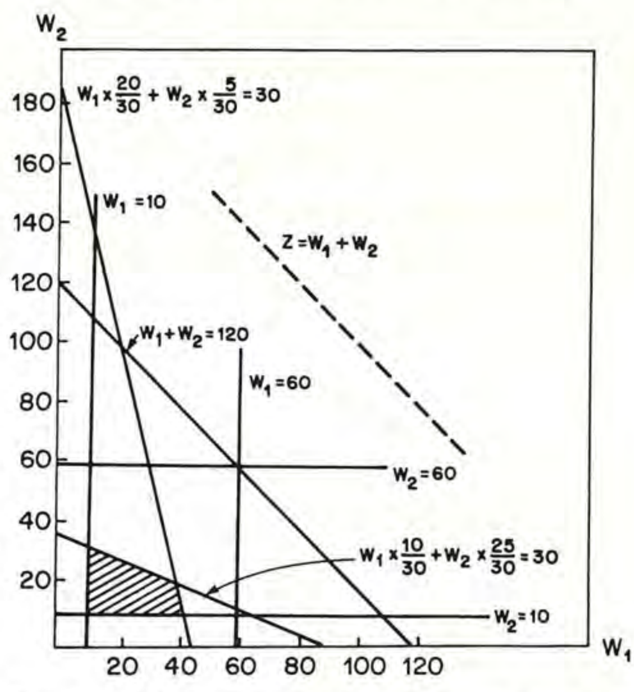


Figure 7. Optimum loading for a container of given dimensions.

(27.3 kg). This is a case that has all the characteristics typical of linear programming models. First, the objective is to maximize the sum of W_1 and W_2. Second, the objective function is maximized subject to a set of linear constraints; two of these are on reactive forces at both hands. The linear programming model can, therefore, be stated as follows (refer to Figure 7).

Maximize:

$$Z = W_1 + W_2$$

Subject to:

$$W_1 + W_2 \leq 120$$

Constraint on total weight of each container.

$$10 \leq W_1 \leq 60$$
$$10 \leq W_2 \leq 60$$

Constraints on individual loads.

$$W_1 \times \frac{20}{30} + W_2 \times \frac{5}{30} \leq 30$$
$$W_1 \times \frac{10}{30} + W_2 \times \frac{25}{30} \leq 30$$
$$W_1, W_2 \geq 0$$

Constraints on hand forces; obtained by taking movements about both ends of the simple beam representing the loading condition for the container.

The above model is very basic and can be solved graphically or by using the simplex method. When the number of variables (loads) exceeds two, however, the simplex method is the algorithm to be used for solving the linear programming model (Hillier and Lieberman, 1974). The optimum solution of the given model yields:

$$W_1 = 40 \text{ lb } (18.2 \text{ kg})$$
$$W_2 = 20 \text{ lb } (9.1 \text{ kg})$$

This solution signifies that the weight per container should not exceed 60 lb. (27.3 kg).The components of any part should be shipped separately if their combined weight exceeds the optimal weight as determined by the model.

Example 5

A group of men perform a lifting task for 6 hr every working day. The task consists of picking boxed machine parts from a floor and positioning them on shelves approximately 30 in. high (765 mm). The weight of the boxes is normally distributed with mean $\overline{S}_D$ and standard deviation σ_{S_D}. Strength capability of the men is also assumed to be distributed normally with mean $\overline{S}_C$ and standard deviation σ_{S_C}. What is the probability that one of the men will attempt to handle a load that exceeds his strength capability?

The problem at hand addresses the very subject of how much safety factor is adequate or acceptable for developing a standard for manual handling tasks. Assuming that the weight (or its biomechanical equivalent, see Example 2) of the object will form the basis for such standard, the question becomes: what is the maximum permissible weight that an individual should be asked to handle? Traditionally, this question has been answered by (1) determining the maximum weight an individual (usually defined in terms of some basic characteristics such as age, weight, etc.) can lift without incurring any physiological or anatomical damage and (2) adjusting this maximum weight by using a safety factor to yield a permissible work load, i.e., a consensus standard. In many instances, however, the inclusion of safety factors in determining the weight limits is achieved indirectly via extensive experimentation as typified by the work of Snook and his co-workers (see Snook et al., 1970). Insofar as lifting is concerned, a variety of recommended maxmum limits exist that, in many instances, are inconsistent (Herrin et al., 1974). We do not, however, wish to launch an inquiry to determine which ones are justified or applicable and which are not. Indeed, our primary purpose here is to underscore the fact that using a sfaety factor (regardless of how it is incorporated) in setting performance standards can, for the most part, be misleading. The following cases will illustrate this point.

As stated in the problem, consider the two variables: strength demand ($\overline{S}_D$) and strength capability ($\overline{S}_C$); both are normally distributed (see Figure 8). For other than normal distribution, a similar procedure can be used; the basic idea would remain intact. The only change would be the outcome of the integration. The area of overlap in Figure 8 determines the probability that the demand will exceed the available strength, i.e., probability of failure P_F.

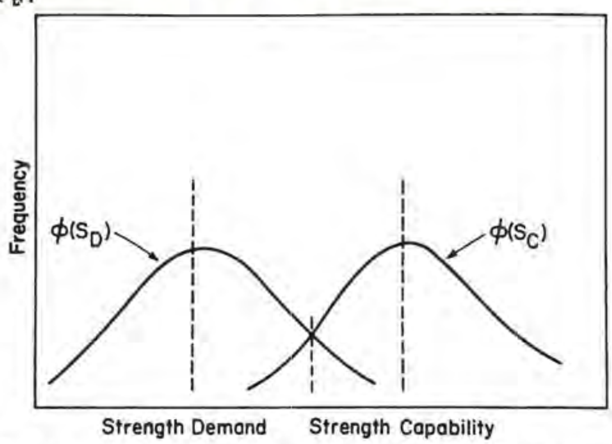


Figure 8. Distribution of strength demand and strength capability.

This probability can be given as

$$P_F = \int_{-\infty}^{+\infty} \phi(S_D)\left[\int_{-\infty}^{S_D} \phi(S_C)\, d_{S_D}\right] d_{S_D}$$

For two normally distributed random variables, P_F is given by

$$P_F = 1 - \int_{-\infty}^{Z} e^{-Z^2/2}\, dZ$$

where

Z = the normalized random variable

$$= \frac{\overline{S}_C - \overline{S}_D}{\sqrt{\sigma^2_{S_C} + \sigma^2_{S_D}}}$$

To illustrate the use of Equation 7, consider the following three cases.

Case 1

Let

$$\overline{S}_C = 3.0\,\overline{S}_D$$

$$\sigma_{S_C} = 0.2\,\overline{S}_C$$

$$\sigma_{S_D} = 0.3\,\overline{S}_D$$

For the given data, we compute Z = 3.33. Using table of normal distribution, the probability of failure is given as

$$P_F = 0.001$$

Case 2

Let

$$\overline{S}_C = 3.0\,\overline{S}_D$$

$$\sigma_{S_C} = 0.2\,\overline{S}_C$$

$$\sigma_{S_D} = 1.0\,\overline{S}_D$$

Similar to Case 1, the given data yields a probability of failure

$$P_F = 0.058$$

Notice that the two cases possess the same safety factor (i.e., $\overline{S}_C/\overline{S}_D = 3.0$); however, they are far from having the same reliability or probability of failure—a result that substantiates the case against the blind use of safety factors in design.

Case 3

Compute the mean strength capability if the probability of failure is to be limited to 0.01%. Assume $\sigma_{S_C} = 1.5\ \overline{S}_D$ and $\sigma_{S_D} = 1.5\ \overline{S}_D$. From normal distribution tables, for a $P_F = 0.0001$, we obtain Z = 3.72. Substituting Z into Equation 7 and solving for $\overline{S}_C$, we obtain

$$\overline{S}_C = 8.89\,\overline{S}_D$$

In other words, a safety factor of 9 would be sufficient if we desire to have practically 100% of the work force succeed in performing their tasks.

CONCLUSIONS

In the preceding examples, an attempt was made to emphasize that the design of containers is basically a problem of mechanics. The use of optimization techniques was also presented as a viable approach for dealing with specific container design problems. Furthermore, the application of a probabilistic approach to the definition of permissible weights for manual tasks seems feasible and thus warrants further consideration. If safety standards for manual tasks are to be practical and meaningful, there is no other alternative than the development of standards that account for the uncertainties associated with man and his performance.

Although a challenge in itself, the design of a container should not, in and of itself, mask the need for using a total approach to the design and evaluation of manual tasks; i.e., consideration of man, task, equipment, environment, and management practices. To this end, the modeling approach in biomechanics stands to contribute the most, since modeling offers the flexibility of studying and analyzing problem variables in integrated and complete fashion (Ayoub, 1975). In addition, modeling confers the potential of bypassing the limitation and difficulties typical of many other approaches, e.g., experimentation.

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MANUAL MATERIALS HANDLING: EFFECTS OF THE TASK CHARACTERISTICS OF FREQUENCY, DURATION, AND PACE

R. L. Burse

INTRODUCTION

The objective of this paper is to review the effects of the task characteristics of frequency, duration, and pace on work output and physiological strain during manual materials handling operations. The emphasis is on manual transfer operations (lifting, carrying, and lowering) of single units or packages of material.

Productivity can be determined rather easily in terms of the amount of material moved within a given length of time, the number of trucks loaded, or some similar measure. Physiological stress is not as readily determined, but its effects are extremely important to the worker. Excessive work stress on the body results in progressively increasing strain throughout the workday. This is shown by working heart rates (HR) that increase throughout the workday (despite whatever rest periods are available), increasing subjective feelings of exhaustion, and, eventually, a decrease in productivity. Several techniques for identifying work stress that exceeds the worker's capability have been presented by Lehmann (1958), Brouha (1960), Müller (1962), and Rohmert (1973a). The approach adopted herein will be that total work stress (with scheduled rest periods) is not excessive, if it results in working HR less than 115 to 120 beat/min after several hours on the proposed work-rest schedule, when no heat or other environmental stress is present. This criterion represents the experience of my laboratory, which is that HR that are elevated, while working, 40 to 50 beat/min above the resting level are tolerable throughout an entire workday, provided they do not progressively increase as a result of additional environmental stress. This criterion is quite in agreement with the criterion of HR $\leq$ 115 beat/min adopted by Snook and Irvine (1966) for materials handling tasks.

Because of the interrelationships that exist between task characteristics, it is necessary to define the variables under consideration. The term "frequency" will be used to mean the number of transfer operations that a worker performs in a given period of time. Frequency is thus inversely related to "duration," which is the length of time required for the performance of a single transfer operation. Frequency seems the most appropriate term in the context of simple vertical lifting or lowering operations, for example stacking or unstacking a pallet. "Duration" seems the most appropriate term to use when discussing carrying operations, wherein a load is lifted, held in the arms against the force of gravity while walking horizontally, and then lifted or lowered into place. The term "pacing" will be restricted to mean the interspersion of rest periods between periods of work in which transfer operations are carried out.

EFFECT OF FREQUENCY

The frequency at which loads can be repeatedly lifted or lowered is, of course, highly dependent upon load weight. Snook and his colleagues (1966, 1968, 1970, 1971, 1974) have provided information concerning the amount of weight that can be moved at a fixed frequency and vice versa. This group has used a combination of the working HR criterion of $\leq$ 115 beat/min and a psychophysical approach, whereby the worker determines the weight or frequency that can be handled continuously throughout the workday without undue exertion, overheating, or fatigue. Their extensive results have been condensed into a series of calculated percentile values for both male and female worker populations.

Table 1. Frequency of lift per minute (f) and productivity in kg/min (P) attainable at different loads by 90% of male workers without undue strain*†.

Load weight (kg)	*Criterion of strain*	*Type of lift* — *Floor to knuckle ht.* f	P	*Knuckle ht. to shoulder ht.* f	P	*Shoulder ht. to arm reach* f	P
9.1	HR <115	—	—	9.0	81.8	6.5	59.1
	vol. max.	—	—	—	—	—	—
15.9	HR <115	2.5	39.8	5.5	87.5	4.5	71.6
	vol. max.	3.1	49.3	5.0	79.5	4.3	68.4
22.7	HR <115	2.5	56.8	3.8	86.4	2.7	61.4
	vol. max.	2.4	54.5	3.8	86.4	3.3	75.0
29.6	HR <115	2.0	59.1	(not possible)		(not possible)	
	vol. max.	—	—				

*Either HR below 115 beat/min or the voluntary maximum sustained for 1 hr.
†After Snook and Irvine, 1966, 1968.

Table 1, from Snook and Irvine (1966, 1968), shows both the frequency of repetitive lift and the productivity in weight of material moved per minute that can be achieved without undue strain by 90% of male workers, ages 20 to 50. Three levels of lift were investigated: floor level to knuckle height, knuckle height to shoulder height, and shoulder height to arm reach overhead. In all cases, each load was actually lifted a distance of 508 mm. In general, the greatest output can be achieved with the least strain when the heavier loads are lifted at a reduced rate, rather than when the lighter loads are lifted at a faster rate. This has also been shown by Hamilton and Chase (1969) for 254-mm (10-in.) lifts from waist level with weights weighing from 4.5 to 11.4 kg. For lifts from floor to knuckle height, the 22.7-kg weight lifted about 2.5 times/min appeared preferable to the lighter loads. For lifts from knuckle to shoulder height, both the 15.9-kg load lifted 5.5 times/min or the 22.7-kg load lifted 3.8 times/min were similarly productive. These two loads lifted at frequencies of 4.5 and 3.3 times/min, respectively, were also the most productive for lifts from shoulder height to arm reach overhead. The close similarity of results from the two different criteria of undue strain indicates that the psychophysical method can predict physiological strain with reasonable accuracy in the thermoneutral environments of these studies.

Table 1 also shows that the lift from knuckle to shoulder height is the most productive at any weight investigated, by margins ranging from 15% to 77%. Materials handling tasks, therefore, should be designed to capitalize on this advantage, if possible. The least productive lift was from floor to knuckle height. This reflects the increased energy cost of raising and lowering the body along with the load, which has been reported to be as high as 120% of the cost of lifting from knee height without raising the body (Havel et al., 1974a).

The lowering of loads a distance of 508 mm was included along with lifting in a later study by Snook et al. (1970). Again the psychophysical approach was used to establish the weight of the load that could be tolerated for an entire workday at several fixed frequencies. The upper portion of Table 2 shows the heaviest loads that could be tolerated by 90% of the male work force at the lowest lifting and lowering rates investigated. Lifting and lowering were done at the three different levels previously discussed. This study also determined the maximum rate of material transfer (output) that could be tolerated by 90% of the work force; this permitted calculating the frequency at which maximum productivity will be maintained, if the maximum tolerable weight is moved each time. These values are shown in the last column.

Both the lifting and the lowering tasks are seen to be most productive when done between knuckle and shoulder height. More weight (2 kg) could be handled when lowering at this level than when lifting, but this difference between lifting and lowering was not seen at either the higher or the lower levels. Clearly, productivity is greater when lowering at all levels, but this is due to the worker tolerating a greater frequency, rather than a greater weight, when lowering from arm reach to shoulder height or from knuckle height to floor level. Havel et al. (1974b) have also shown the energy cost and the as-

Table 2. Maximum weight (kg) and maximum productivity (kg/min) acceptable to 90% of male and female workers for lifting and lowering throughout the workday, with associated mean HR values.*

Height of transfer	*Type of transfer*	*Max. weight (kg)*	*Max. productivity (kg/min)*	*Mean HR (beat/min)*	*Frequency† (per min)*
Male workers:					
Floor level to knuckle ht.	lift	16.9	57.0	112	3.4
	lower	16.4	84.8	119	5.2
Knuckle ht. to shoulder ht.	lift	15.6	90.1	105	5.8
	lower	17.7	117.5	104	6.6
Shoulder ht. to arm reach up	lift	13.4	55.6	100	4.2
	lower	13.0	69.5	109	5.3
Female workers:					
Floor level to knuckle ht.	lift	12.7	47.7	117	3.7
	lower	13.6	82.6	126	6.0
Knuckle ht. to shoulder ht.	lift	11.4	74.4	107	6.6
	lower	11.8	114.2	100	9.7
Shoulder ht. to arm reach up	lift	10.9	57.0	101	5.2
	lower	10.9	83.9	105	7.7

*From data of Snook et al., 1970; Snook and Ciriello, 1974.
†Frequency to maintain maximum productivity if maximum weight is handled.

sociated HR to be significantly less for lowering than for lifting when the same productivity was maintained.

The data from Tables 1 and 2 suggest that, for 90% of the male work force, loads less than 16 kg are readily handled between shoulder height and the floor. The maximum frequency per minute when lifting should not exceed 3.5 between the floor and knuckle height or 5.5 between knuckle and shoulder height. When lowering, the frequency should not exceed 6.5 between shoulder and knuckle height or 5.5 between knuckle height and floor. The weight to be transferred between shoulder height and arm reach overhead should not exceed 13 kg, and the frequency should not exceed 4.5 when lifting and 5.3 when lowering.

Jørgensen and Poulsen (1974), in a study of lifting from floor to knuckle height, used two other criteria to determine maximum weight and frequency of repeated lifts: the lifted weight should not exceed 50% of the maximum weight that could be lifted without causing the spinal column to flex; and the sustained energy cost of repeated lifting should not exceed 50% of the individual's maximum aerobic capacity. From their study of two male subjects, they recommend, for 20-year-old men, 26.5 kg lifted three times per minute for short (160 cm) individuals and 33.5 kg at the same frequency for tall (180 cm) men. Presumably individuals of intermediate stature select intermediate weight. For 55-year-old men, the recommended frequency of lift is reduced to twice per minute, but at the same weight. However, Snook (1971) found no significant differences between 14 men aged 25 to 35 and 14 men aged 45 to 60 in either the weight they could handle at a given frequency or the HR induced by repeated lifting at these frequencies. He also found no significant relationship between the weight of load handled repeatedly and the individual's physique. It is therefore likely that the lower weights selected by Snook and colleagues as suitable for 90% of the male work force already compensated for any physique or age differences, and that no further allowance in either weight or frequency was required. The values by Jørgensen and Poulsen may be more representative of the average individual, rather than a lower limit.

Hamilton and Chase (1969) have shown that shifting 4.6- to 11.4-kg cartons between waist level conveyors (with a 10-in. lift) has a 5% to 15% lesser energy cost and associated HR for the same productivity if heavier weights are shifted less frequently. Based on their sample of six men, 11.4 kg can be shifted up to 9 times/min; 9.1 and 6.8 kg up to 12 times/min; and 4.6 kg up to 15 times/min without exceeding an energy cost of 7 kcal/min (490 W) or a HR above 120 beat/min.

Women have a smaller muscle mass than men, because of their generally lower body weights and higher percentage body fat. They also have a lower aerobic work capacity (Åstrand, 1960). Thus it is unreasonable to expect that lifting criteria applicable to 90% of the male work force will also be suitable for the female work force. Snook and Ciriello (1974), using the psychophysical approach, studied 15 well-trained female industrial workers to determine the maximum weight they would lift repeatedly and their maximum voluntary productivity (kg moved per minute). Their suggested weight and productivity limits suitable for 90% of the female work force are shown in the lower part of Table 2, along with the calculated frequency of repeated lift, if maximum productivity is to be achieved throughout the workday while lifting the maximum tolerable weight. In general, women can lift or lower about 2 to 5 kg less than men, but at the same or slightly higher frequencies. Like men, women are most productive in transfer operations between shoulder and knuckle height. Unlike men, however, they appear to be able to handle heavier weights between the floor and hand height than between knuckle and shoulder height. Women differ most from men in the weight they can handle in the shoulder- to-knuckle-height region (about 4 to 5 kg less) and least in the shoulder to overhead reach region (about 2 kg less). The difference in the region from floor to knuckle height is about 3 kg less.

The reported average HR for repeated transfer operations performed by this sample of women were all less than 115 beat/min, except for transfers in the region from floor to knuckle height (which also elicited the highest HR from men).

The previously cited study by Jørgensen and Poulsen (1974) also included two women. The authors suggested weight and frequency limits for lifting by women, based on age and stature. For the 20-year-old, three lifts/min are suggested at weights of 13 kg for the short (150 cm) individual and 17.5 kg for the tall (170 cm) individual. At age 55, the frequency should be reduced to twice per minute and the weight reduced by 2 kg, to 11 and 15.5 kg for the short and tall individual, respectively. The suggested lower limits for weight are quite similar to those of Snook and Ciriello (1974), but the frequency limits are less by a factor of 2 to 3. No HR data were reported by Jørgensen and Poulsen, but their suggested limits of 50% of the maximum aerobic capacity should result in HR equal to or slightly exceeding that reported by Snook and Ciriello. Why these responses should occur at markedly lower lifting frequencies is not clear. Whether or not the load should be modified for women of different ages and stature has not yet been established as no one has yet reported whether or not female lifting capabilities are correlated with either age or physique, as was done for men by Snook in 1971 (see, however, M. M. Ayoub et al. in this symposium). Petrofsky et al. (1975) have shown that women have a significant decline with increasing age in both absolute and relative strength (and an increase in relative endurance), which is most pronounced after age fifty. On the other hand, the comparison sample of 100 men showed no significant decline in strength or increase in endurance with age. In their twenties, women had 65% the strength of men the same age; in their thirties, 57% ; in their forties, 60% ; and in their fifties, 50% . When in their twenties, the endurance of women was 112% that of men; when in their fifties, it had increased to 140% that of men. Whether findings concerning gripping strength are applicable to the other muscle groups involved in lifting cannot be stated with certainty. However, the figure of about 60% for the relative isometric strength of women has also been reported for other muscle groups (see Rohmert and Jenik, 1973, and the succinct review by Snook and Ciriello, 1974), and the higher lifting frequencies for women shown in Table 2 are certainly consonant with a greater muscular endurance. Therefore, it seems prudent to recognize that lifting strength of female workers in their fifties may be 10% to 15% less than that of their younger counterparts. However, it is likely that the values proposed by Snook and Ciriello (1974) for 90% of the female work force do, in fact, adequately compensate for any decline in strength with age.

Suggested limits for both maximum weight and frequency for lifting and lowering are summarized in Table 3 for 90% of the male and female work force. These limits are intended for healthy, but otherwise unselected, individuals. Also included are the mean HR values reported by Snook and Ciriello for handling the same, or greater, weights. All the frequency limits and a number of the weight limits are based on the values given in Snook and Irvine (1968), Hamilton and Chase (1969), Snook et al. (1970), Snook (1971) and Snook and Ciriello (1974), rather than from Jørgensen and Poulsen (1974), whose sample size was only two of each sex and thus might not be as representative of the work force. Values in excess of these limits should re-

Table 3. Suggested standards for maximum weight and frequency to maintain the maximum productivity acceptable to 90% of unselected male and female workers for lifting and lowering throughout the workday, with the expected upper limits to HR.*

Height of transfer	*Type of transfer*	*Sex*	*Max. weight (kg)*	*Frequency (transfers/min)*	*Expected HR less than*
Floor level	lift	M	16	3.4	112
to knuckle		F	12	3.7	117
ht.	lower	M	16	5.2	119
		F	12	6.0	126
Knuckle ht.	lift	M	16	5.8	105
to shoulder		F	11	6.6	107
ht.	lower	M	16	6.6	104
		F	11	9.7	100
Shoulder ht.	lift	M	13	4.2	100
to arm		F	11	5.2	101
reach up	lower	M	13	5.3	109
		F	11	7.7	105

*After data of Snook and Irvine, 1968; Snook et al., 1970; Snook and Ciriello, 1974.

quire medical evaluation, as suggested by Snook (this symposium) for the lower of his "Zone 2" lifting limits. It is hoped that these suggested limits will be evaluated in both experiment and practice to determine if they are within the capacities of 90% of the unselected male and female work force, as intended, and that they do not result in progressively increasing HR or subjective fatigue throughout the workday.

CARRYING

Many materials transfer operations involve carrying as well as lifting or lowering. There are many reports of the energy cost of carrying loads in the hands or loads attached to the body. Unfortunately, most of these reports are of the physiological response to relatively long-term load carrying performed at constant walking speeds, rather than of short "shuttle-type" carries typical of industry. However, the maximum tolerable loads, productivity, and average HR of both males and females performing shuttle-type, two-handed carries for 2.1, 4.3, and 8.5 m have been reported by Snook (1971) and Snook and Ciriello (1974), and are shown in Table 4. In addition, the frequency of carry and the resulting trip duration (to the nearest second) needed to maintain maximum productivity when the maximum tolerable load is carried have been calculated. If the load is configured such that it must be carried with bent arms, rather than straight arms, the weight must be reduced 3 to 5 kg for men and 2 to 3 kg for women. The duration of carry apparently remains the same for a given distance, however, irrespective of weight. This suggests a preferred rate of movement, with the work load adjusted by varying the weight transported.

One-handed lifting, holding, and carrying by 10 men has been reported by Drury (1976). His subjects were willing to carry only two-thirds the weight that they were willing to lift and hold for the same length of time. For compact loads of suitcase-type construction, balanced fore and aft, and requiring a handle-to-leg clearance ≤ 11 cm, 30 kg will be carried for 10 sec, 25 kg for 20 sec, 21 kg for 40 sec, 18 kg for 60 sec, 15 kg for 80 sec, 13 kg for 100 sec, and 11.3 kg for 2 min. The report also contains factors to be applied to Drury and Pfeil's (1975) prediction model for maximum weight of lift for less compact, or more awkward, loads. Also reported is a study in which six men carried loads one-handed. This study showed that if two equal loads of a given weight are carried, one in each hand, the combined loads will be carried the same distance as a single load of half the total weight carried in one hand. The two arms thus appear to act independently of each other in a one-handed carry, perhaps because equal loads in each hand balance each other without requiring added static muscular effort by the torso.

PACING

The literature on pacing, or interspersing rest pauses between periods of work, is too extensive to be reviewed in detail here. Excellent general synopses are available in Brouha (1960), Grandjean (1969), Lehmann (1958) and Rohmert (1973a and b). A few points require emphasis, however. Work in thermoneutral environments that results in HR less than 115 to 120 beat/min can usually be performed without rest pauses other than an hourly break for personal needs. Work of a heavier nature can generally be made tolerable throughout an entire workday by interspersion of rest pauses, such

Table 4. Maximum weight (kg) and maximum productivity (kg-m/min) acceptable to 90% of unselected male and female workers for repeated horizontal carry, with associated mean HR.*

Sex and arm position	*Length of carry (m)*	*Max. weight (kg)*	*Max. productivity (kg-m/min)*	*Mean HR (beat/min)*	*Frequency of carry† (per min)*	*Duration of carry (s)*
Male,	2.1	21.8	289	101	6.2	10
straight	4.3	20.0	340	100	4.0	15
arm	8.5	19.1	390	101	2.4	25
Female,	2.1	15.0	269	106	8.4	7
straight	4.3	14.5	318	104	5.1	12
arm	8.5	14.5	328	110	2.6	23
Male,	2.1	18.2	230	103	5.9	10
bent	4.3	16.4	271	103	3.9	15
arm	8.5	14.5	295	103	2.4	25
Female,	2.1	12.7	223	109	8.2	7
bent	4.3	12.7	250	108	4.6	13
arm	8.5	11.4	303	111	3.1	19

*From data of Snook and Ciriello, 1974.

†To maintain maximum productivity if maximum weight is handled.

that the time-weighted average for the energy expenditure does not exceed 40% to 50% of the individual's maximum aerobic capacity. This represents about 7kcal/min (490 W) for 70-kg males, and 4.5 kcal/min (315 W) for 55-kg females with a maximum aerobic capacity 65% that of males (Åstrand, 1960). The literature on exercise physiology is quite clear on the point that, for an equal duration of rest, many short pauses are far superior to fewer long pauses in preventing buildup of lactic acid and exhaustion. For example, heavy bicycle work (which has a large component of static muscular effort, like lifting and carrying), done for 1 hr with alternate work and rest periods of 3 min, had a working HR of 188 and a blood lactic acid concentration of 120 mg %, with the subject near exhaustion (Åstrand et al., 1960). The same load done for 1 hr, with work and rest periods of 30 sec, had a working HR of 150 and a lactic acid concentration of 20 mg %, with no apparent exhaustion. For a fixed amount of bicycle work done for 1 hr, either continuously at lower workloads or discontinuously at higher workloads, with rest periods varying from 0.75 to 6 min, the efficiency of work was the same (Christensen et al., 1960). These findings suggest that brief periods of rest following brief periods of work permit the dissipation of metabolic products before they are able to build up to fatiguing levels. These periods also permit the replenishment of local stores of oxygen for aerobic metabolism so that the muscle minimizes the requirement for anaerobic metabolism, with no reduction in efficiency. These findings appear quite relevant to the problem of exhaustion during manual materials handling, since lifting and holding a load requires that muscles shorten and remain shortened for a period of time. (This is sometimes called static work.) Since muscle cells are isovolumetric during contraction, they get fatter as they shorten and occlude the blood vessels that provide their metabolic nutrients. The greater the percentage of maximum force exerted by a muscle, the greater the occlusion of blood flow to (and through) that muscle, until flow is completely blocked at about 70% of maximum isometric force. Thus, short bouts of predominantly static work interspersed with short rest periods will assist dramatically in maintaining blood flow to the muscles used in manual lifting and thereby retard exhaustion.

Monod and Scherrer (1965) developed the concept of a "critical force" in static muscular work, which, if exceeded, will result eventually in exhaustion. The critical force is higher for intermittent than for continuous static work. For half work and half rest, the critical force is 40% of the maximum isometric force. Work at forces exceeding the critical force is thus time-limited, but the amount of force that can be exerted for a given period of time is from 1.4 to 1.6 times greater for 50-50 intermittent work and rest than it is for continuous work. Unfortunately, the influence of the duration of each work-rest cycle was not included in the report, nor was the effect of work-rest ratios other than 50-50.

The allowances for rest pauses now used by one British corporation, based upon the weight lifted or the force exerted, have been published by Williams (1973) and are reproduced in Table 5. These allowances were originally adopted from available information in the literature and have been modified by practical experience within the corporation. The basic percentages for weight of lift

Table 5. Allowance for rest pauses, as percent of time working, in relation to weight lifted or force exerted.*

Weight or force (kg)	Rest pauses (percent of work time)†	
	Short duration	*Long duration*
up to 2.4	0.0	0.0
2.5 — 4.3	1.0	2.0
4.4 — 7.0	2.0	3.5
7.1 — 9.3	3.0	5.0
9.4 — 11.5	4.0	7.0
11.6 — 13.8	6.0	9.0
13.9 — 16.1	7.5	11.0
16.2 — 18.3	9.0	13.0
18.4 — 20.6	10.5	15.5
20.7 — 22.9	12.0	18.0
23.0 — 25.1	13.5	20.5
25.2 — 27.4	15.0	23.0
27.5 — 29.7	16.5	25.5
29.8 — 32.0	18.0	28.0
32.1 — 34.3	19.5	30.0
34.4 — 36.5	21.0	32.0
36.6 — 38.8	22.5	34.0
38.9 — 41.1	24.0	36.0

*From Williams, 1973.

†Short duration = force exerted for 6 seconds or less; long duration = force exerted for more than 6 seconds. Add 7% for level or downhill carry and 10% for uphill carry.

(or force exerted) are increased by an additional 7% if the load is to be lifted while bending or stooping or is to be carried on the level or down slope, and by 10% if the load is to be carried over rising ground or up steps, stairs, or ladders. The "short duration" is for typical transfer operations, each requiring 6 seconds or less; the "long duration" is for operations longer than 6 seconds, but no upper limit was specified. From the work rest studies cited earlier, the total rest time apparently should be spent in frequent short breaks rather than a single long one.

There is no specific requirement that work or rest periods must be of uniform length, if an advantage is otherwise gained. Brouha (1960, p. 125) cites a case whereby the progressive increase in HR seen throughout the workday in a truck loading operation under heat stress was prevented by the adoption of a somewhat unusual work-rest schedule. The original schedule was to load six trucks during each half of the day shift, resting after each truck. The revised schedule was to load eight trucks in the coolest part of the day: load four trucks from 8:00 to 9:30, rest 45 min; load four trucks from 10:15 to 11:15, take a 75 min rest and lunch break; load two trucks from 12:30 to 2:00, rest 30 min; and load the last two trucks from 2:30 to 3:30.

The available information on work output in general suggests that manual materials handling tasks are best kept within the capabilities of the work force by taking frequent short breaks and allowing the worker, where possible, to vary the weight handled in order to maintain his preferred rate and frequency of movement. It is hoped that the information presented in this paper will serve as a stimulus, not only for further research, but also for the development of provisional work standards.

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ENVIRONMENTAL CHARACTERISTICS

E. Kamon

INTRODUCTION

The environmental characteristics of a workplace are usually considered in terms of their potential for disrupting work, either by reducing productivity or by affecting the well-being of workers. Unfavorable conditions disturb the equilibrium between a worker and his environment and are perceived as discomfort. If this persists, it can lead to accidents. Disturbing environmental factors include thermal conditions and airborne irritants. In general, these factors can be considered as having long-term effects but are most likely to have immediate effects by impairing work. The immediate effects, as they are reflected in the physiological responses to the environment, will be considered in this presentation.

This paper will focus mainly on the hot environment in relation to manual material handling and will draw on observations from the laboratory as well as the field. The protection of workers against cold environment has received less attention than the protection against heat, despite the fact that many workers are exposed not only to natural but also to man-made cold environments. Therefore, only some aspects of exposure to cold will be included. Acclimation to the environment will not be discussed. It will be assumed that the workers were exposed long enough to the environment in question to be considered physiologically well adjusted to it. Finally, some of the few observations on the effect of airborne material on physical performance will be presented.

HEAT STRESS

The Problem

It is difficult to assess the strain due to physical work under hot ambient conditions. The main problem is that the stresses due to physical work and a hot environment are both indicated by common physiological responses such as rise in the body's temperature, blood redistribution between the internal organs and the peripheral system, and increment in heart rate. By using the same apparent physiological responses as strain criteria, the two stresses (physical work and heat) are considered equally effective. Actually, they are not.

Although the effect of heat stress can be considered in absolute values, that for physical work is relative. Responses to the heat load imposed by the environment are directly related to the absolute heat accumulating in the body. The responses to physical work are relative to the individual's maximal strength and his aerobic capacity (aerobic power). These, in turn, are dependent upon factors such as physical fitness, age, and sex. Consequently, only after the strain due to the physical work is established can the effect of the expected strain due to heat be shown. This will be described in some detail in the following examples in which the stresses caused by heat and those related to physical work capacity are discussed.

Total Heat Load

The stress factor is actually the state of the balance of heat exchange between the worker and his environment. When heat exchange is balanced, there is no change in the body's heat storage. By itself, the heat balance is a straightforward situation governed by the heat transfer laws. The avenues of heat transfer are radiative (R); convective (C); and evaporative at the skin surface (Esk). Including the metabolic heat source (M), the heat balance is usually described in this simple form:

$$M \pm (R + C) = Esk$$

This indicates that while R and C can be avenues of either heat loss or heat gain, M is always a source of heat gain. Esk is always an avenue for heat loss. Evaporation is dependent on the ambient capacity to absorb water vapor (E_{max}). Thus, the balance of heat exchange becomes $M + R + C = E_{max}$. By now the coefficients applicable to each of these avenues are well established. The practical formulae for computing the heat exchange are summarized in the Appendix.

Physical Work Capacity

Here exercise is a more precise term than work because it implies rhythmic muscular contractions involving at least 50% of the body's musculature. Currently, the most accepted view is that man's exercise, or working, capacity reflects the ability of the cardiovascular system to deliver ambient O_2 to the working muscles. Therefore, the maximal O_2 uptake (V_{O_2} max) during work represents the cardiovascular functional capacity for an individual. In the healthy individual, V_{O_2} max is accompanied by maximal attainable HR (HR max).

The notion of relative O_2 uptake ($\dot{V}_{O_2}$) is gaining ground among physiologists who are interested in standardizing measurement of strain. For example, a job requiring a V_{O_2} of 1.5 l/min having the energy equivalent of 522 $\dot{W}$ is only 50% of $\dot{V}_{O_2}$ max for a normal young man in his twenties, but is at the maximal level (V_{O_2} max) for a normal female worker in her forties. Since the adjustments of the circulatory system to work is proportional to its functional capacity, the HR will be submaximal for the male worker, but maximal for the female. Consequently, endurance and recovery time will differ for the two workers. For the male, 40 to 50 min work and 10 to 15 min rest will be acceptable without undue fatigue during a whole shift. For the female, however, 5 min work with at least 30 min rest might be still a fatiguing schedule.

The following observations concerning physical work capacity have also been made: 1) $\dot{V}_{O_2}$ max is sex- and age-dependent and can be kept at a higher than average level by physical conditioning. 2) $\dot{V}_{O_2}$ max drops yearly by about 0.4 ml/kg•min, from a norm of 38 to 42 ml/kg•min, at age 25 (Dehn and Bruce, 1972). 3) Woman's $\dot{V}_{O_2}$ max is less than man's (Åstrand and Rodahl, 1970). 4) Since HR is linearly related to relative $\dot{V}_{O_2}$, the steady state HR is predictable from the $\dot{V}_{O_2}$ max and the job's metabolic requirements provided ambient conditions are neutral. It should be noted that prolonged work involves a slight rise in HR, mainly because of the need to maintain core body temperature, but a reasonable steady state is expected for a given relative V_{O_2} (% V_{O_2} max).

Criteria of Strain

Body core temperature and heart rate are the most used measures of strain because of the feasibility of measuring them. Therefore, a short review of the current knowledge on their relation to physical work and heat seems necessary.

Core Body Temperature

During submaximal work, the core body temperature rises at a slower rate when compared with that apparent for O_2 uptake or heart rate. Nevertheless, core temperature (Tc) also reaches a steady state at levels dependent on the intensity of work. Similar to HR, core temperature differs among individuals performing a given work load.

Individual differences cancel when core temperature is related to relative V_{O_2} (% V_{O_2} max). The linear relationship between rectal temperature (Tre) and % V_{O_2} max is shown in Figure 1 for Tre from the 45th to 60th min of work. These values were obtained under unstressful ambient conditions, and the subjects were in above-average conditions of fitness: some could sustain work at 70% to 80% $\dot{V}_{O_2}$ max for more than 30 min.

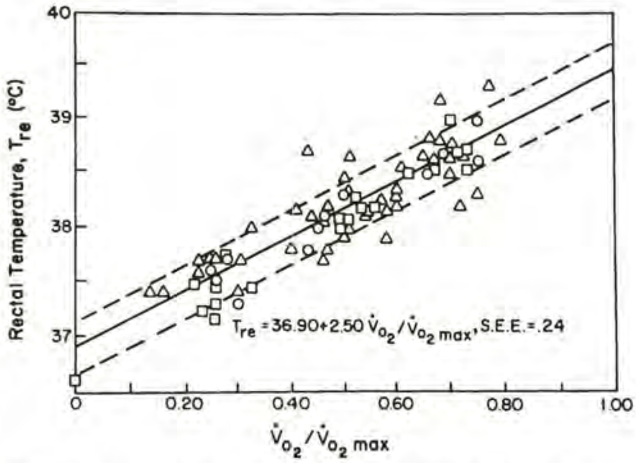

Figure 1. The relationship between rectal temperature and relative O_2 uptake ($\dot{V}O_2$ as a fraction of $\dot{V}O_2$ max) under temperate ambient conditions (partially adapted from Saltin and Hermansen, 1966).

Heart Rate

The linear relation between HR and $\dot{V}_{O_2}$ is standardized in terms of $\dot{V}_{O_2}$ as a fraction of $\dot{V}_{O_2}$ max. Roughly the following quantitative values apply: 1) At 50% V_{O_2} max, HR is 128 bpm and 132 bpm for men and women, respectively, at age 25 (Åstrand and Rodahl, 1970); 2) Age reduction in maximal HR is of the order of 7 to 10 bpm every decade (Am. Heart Assn., 1972). Slight age reduction in the HR for work at 50% V_{O_2} max is also expected, but for all practical purposes, it can be ignored.

At low work levels, the heart stroke volume (SV) is submaximal. Maximal SV are reached at exercise levels demanding 40% V_{O_2} max (Astrand and Rodahl, 1970). Cardiac output (CO) is a function of HR × SV and is progressively increasing with the exercise level. At low work loads, increased HR does not represent the increase in CO and V_{O_2}. However, from work at about 40% $\dot{V}_{O_2}$ max, HR is linearly related to the increase in % $\dot{V}_{O_2}$ max. For all practical purposes, the linearity between

HR and % $\dot{V}_{O_2}$ max can be assumed from 33% $\dot{V}_{O_2}$ max at HR of 100 bpm up to $\dot{V}_{O_2}$ max at HR max for men, and from 33% $\dot{V}_{O_2}$ max at HR 110 bpm up to $\dot{V}_{O_2}$ max at HR max for women. In summary, under neutral ambient conditions, the upper 67% $\dot{V}_{O_2}$ max extends between 100 bpm (or 110 bpm) to 190 bpm at age 20 and decreases with age to between 100 bpm (or 110 bpm) and 170 bpm at age 50, depending on the sex of the worker.

It should be noted that in manual material handling the activity deviates from the rhythmical muscular contractions of exercising man, in that some extra static postural muscular action is involved and relatively longer periods of contraction are expected from the arm muscles. Such deviation is most likely to introduce additional cardiovascular involvement for a given V_{O_2} and is most likely to reduce $\dot{V}_{O_2}$ max. Petrofsky (personal communication) found that $\dot{V}_{O_2}$ max for repetitive lifting from floor to waist height is 15% to 35% lower than that observed in the same subjects during cycling, depending on the weight lifted. The heavier the weight, the lower is $\dot{V}_{O_2}$ max. This means that manual material handling is relatively more strenuous than rhythmical exercise; this is especially important when additional stresses of heat are involved.

Summary

Heart rate and core body temperature may best be used as criteria for evaluation and prediction of strain for the following reasons: 1) they are relatively easily measured; 2) their functional limits are known; 3) under neutral ambient conditions, the magnitude of their responses are proportional to the relative V_{O_2}; 4) thermal stress, as an addition to work, raises HR and Tc in proportion to the absolute value of the total heat load. The baseline value at neutral ambient conditions (but relative to $\dot{V}_{O_2}$ max) and the absolute increase due to heat stress combine the two concepts of a) the dependency of physiological responses (the strain) or M as a fraction of V_{O_2} max and b) the absolute value of M plus the gain from the existing external heat loads (R + C). However, since the cardiovascular system has to meet the combined demand of O_2 delivery to the working muscles and heat transport to the skin, the magnitude of relative strain due to work serves as the baseline. The estimate of the reserve available for heat transport should be found in the range between the baseline and the maximal obtainable value. In other words, if a given task is closer to one worker's maximal capacity than to another's, the reserve of the former for heat transport is smaller than that of the latter.

Laboratory Observation

Load Carrying

In an attempt to define the optimal weight for hand carrying, we have designed an experiment with a loaded 30- × 40- × 30-cm carton. The details are given elsewhere (Kamon, 1972). Briefly, 36 combinations of walking speeds, weight carried, and ambient temperatures were tested (Figure 2). Each experiment lasted 65 min, including a 10-min warmup walk, 5-min rest, and a thrice-repeated sequence of three consecutive 5-min periods of carrying, walking, and resting, as shown in Figure 3.

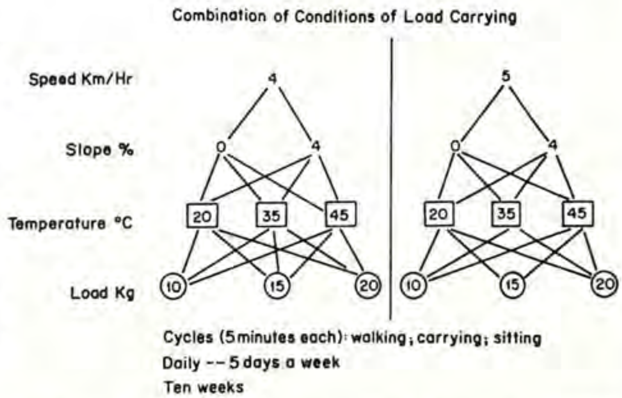

Figure 2. The combinations of treadmill speed and inclination, the load carried, and the ambient temperatures used in the load-carrying experiments.

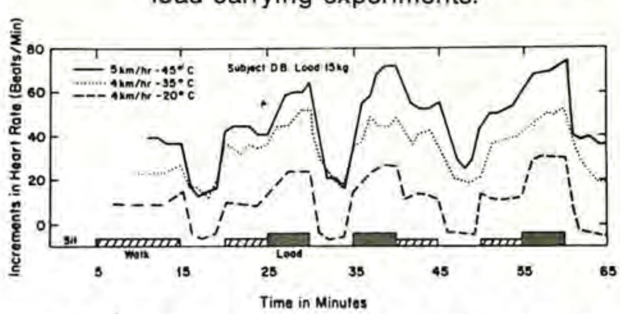

Figure 3. Increments in heart rates above sitting at 20°C ambient temperature during three cycles of walking, load-carrying, and sitting.

First, it should be noted that no changes were observed in M for the different ambient temperatures (Ta). Linear correlation was found between the load carried and M at each walking condition (Figure 4). This constant M for each work load was important in our observation of the cardiac cost represented by the increment in heart rate (HR) de-

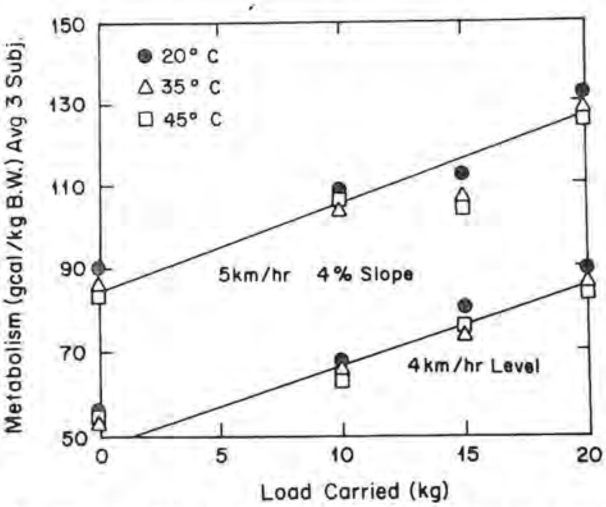

Figure 4. The linear relationship between load carried and metabolic rate.

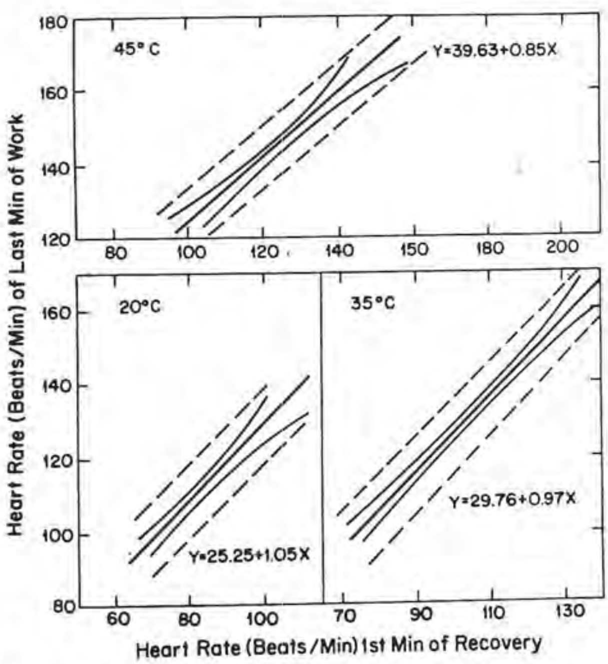

Figure 5. The linear relationship between the heart rate during the last minute of work and the heart rate during the first minute of recovery for work under the three air temperatures.

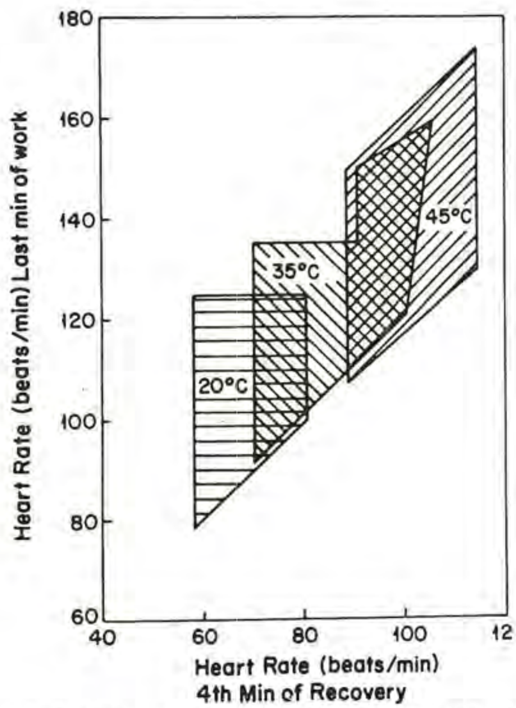

Figure 6. The overlap in the relationship between the heart rate during the last minute of work and the heart rate during the fourth minute of recovery for three air temperatures.

scribed in Figure 3. This typical example demonstrates for manual material handling what Brouha (1967) already observed in rhythmic exercise such as cycling: namely, that increments in HR are a function of Ta and that excessive strain due to work and heat prevents levelling off in HR. Figure 3 shows that for carrying 15 kg (we found this to be the optimal weight) at 4 km/hr, HR did level off at 20°C and at 35°C Ta. However, it progressively rose during each cycle and from cycle to cycle at 5 km/hr with 45°C Ta. We showed that the increment due to Ta averaged 10 bpm for a rise of 10°C in Ta with low humidity; the strain of the work load (20 kg on level and 10 to 15 kg uphill) had a creeping effect of about 3 bpm per cycle, and the strain of the combined work load and heat load (15 to 20 kg under 45°C) had a creeping effect of 5 bpm per cycle. Furthermore, high Ta impaired the recovery rate. Figure 5 shows that the first minute recovery HR remained higher as Ta rose from 20° to 35° and to 45°C. At high Ta, recovery HR was sustained at high levels up to the fourth minute, especially for the cycles where heavier load and uphill walking were involved, as is shown in Figure 6. It should be recalled that Brouha (1967) attributed importance to the recovery HR as a strain indicator, in particular as it was manifested in a drop during the first 3 min.

Relative Work

The strain due to the relative stress imposed by a given work load is best demonstrated in the following example that compares men to women in a laboratory experiment. Four female and four male college students comprised the two groups whose characteristics are summarized in Table 1. The

Table 1. Characteristics (mean ± standard deviation) for the participants in study on limits of work under hot, humid environments.

Group	No.	Age (yr)	Height (cm)	Weight (kg)	Surface area (m^2)	$\dot{V}_{O_2}$ uptake: $\dot{V}_{O_2}$ max (ml/kg-min)	$\dot{V}_{O_2}$ max for walking* (ml/kg-min)	% $\dot{V}_{O_2}$ max
Males Clothed	4	22.6 ± 3.6	177.7 ± 3.1	71.4 ± 6.5	1.82 ± 0.10	53.28 ± 8.24	14.80 ± 1.31	25.6 ± 5.1
Females Clothed	4	22.3 ± 2.6	161.9 ± 2.4	60.4 ± 14.8	1.67 ± 0.16	40.21 ± 5.18	17.40 ± 2.80	43.5 ± 7.0
Semi-clothed							12.03 ± 2.11	30.0 ± 5.3

*Males, at level 5.6 km/hr.
Females, inclination adjusted at 4.8 km/hr.

men were subjected to one work load of level walking at 5.6 km/hr that demanded energy cost of 197 W/m² and about 26% of $\dot{V}_{O_2}$ max. Because work load at such an M level would demand a higher % $\dot{V}_{O_2}$ max from the women, they were tested at two different work loads. The first load, achieved by adjusting the speed and slope of the treadmill for each woman, demanded an M similar to that of the men during their work (197 W/m²), but at higher % $\dot{V}_{O_2}$ max (43.5%). The second work load was level walking at 4.8 km/hr that demanded % $\dot{V}_{O_2}$ max close to that of the men (30%), but at lower M (152 W/m²).

The purpose of the study was to define empirically the humidity limits of work under different Ta's ranging from 36°C to 52°C. The procedure is described elsewhere (Belding and Kamon, 1973). In short, each test involved 1 hour of work at a subcritical ambient water vapor pressure (Pwa) to ensure levelling off in Tre and HR. Usually, Tre levelled off within 40 to 50 min. At the end of the first hour, Pwa was raised by 1 Torr every 10 min until Tre inflected upward.

The upward inflection of Tre defined the critical Pwa. Since the critical Pwa was reached 20 to 40 min into the second hour, a long, sustained levelling off in Tre and HR could be observed for the subcritical Pwa values at each Ta tested. These subcritical Pwa values represented the "prescriptive zone" (Lind, 1963). The loci of the mean critical Pwa defined the limit of exposure on the psychrometric chart.

Figure 7 shows two limit lines for the experiments involving the three work loads. The loci of mean critical Pwa for the women and the men who worked at the same absolute value of M (197 W/m²) were close enough to be described by one common line. However, since the women worked at a higher % $\dot{V}_{O_2}$ max than did the men, their steady state HR and Tre were higher, which indicated more strain (see Table 2). When the women worked at lower M (152 W/m²) but at a % $\dot{V}_{O_2}$ max close to that of the men, the HR and Tre of both groups were similar (Table 2). However, because of the

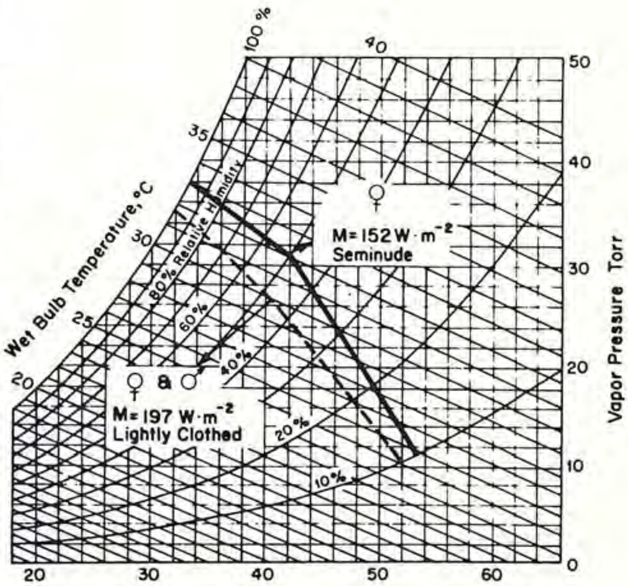

Figure 7. Psychrometrically described limits, beyond which rectal temperature inflects upward for males and females working at different metabolic rates.

Table 2. Means (± standard deviation) of heart rates (HR) and rectal temperature (Tre) at the Tre inflection point for the two groups exposed to ambient temperatures between 36°C to 52°C at the indicated metabolic rate (M).

Group	M (W/m^2)	$\dot{V}_{O_2}$ (% max)	HR (bpm)	Tre (°C)
Males	197	26	106 ± 11	37.7 ± 0.2
Females	152	30	117 ± 13	37.8 ± 0.3
Females	196	44	139 ± 13	38.0 ± 0.2

women's lower M, the loci of the mean Pwa were higher, as Figure 7 shows. It should be noted that at the lower M the women were seminude. This probably raised the Pwa for the limit line somewhat more than the expected elevation due to M only. These observations led to the conclusion that whereas the absolute value of M defines similar biophysical boundaries, the relative M ($\dot{V}_{O_2}$ max) defines the degree of the strain that the individual experiences. HR serves as a good indicator for existing strain or of when workers abstain from excessive strain. This was shown by Snook and Ciriello (1974) who found that workers will reduce their work pace in manual material tasks to compensate for the elevation in HR due to hot ambient conditions. The work rate was reduced 11% to 20% compared with the rate under temperate ambient conditions; this reduced rate was not enough to maintain the HR at the same levels as would obtain in cooler conditions. HR was 9 to 10 bpm higher than under the temperate ambient conditions.

Laboratory and Field Observation

Combined laboratory measurements and field observations confirmed the relationship between low fitness and high cardiac cost (HR) on the job. Minard et al. (1971) conducted a study on open-hearth workers in a steelmill. The field observations included continuous measurements of HR during a shift in which manual material handling, sometimes under extremely high ambient temperatures, accounted for about 50% of the shift period. The laboratory study included HR measurements during a steady-state, standard submaximal bicycle exercise (125 W) under temperate ambient conditions (23°C). As shown in Figure 8, reasonably good correlation was found between the HR for the standard exercise and the mean HR for the whole shift. In other words, workers with a high HR during the standardized exercise, which is indicative of low aerobic power, showed higher cardiac cost on the job.

Field Observations

Recently, a number of field studies have been reported in which stress on the workers was quantified by measuring or estimating the metabolic cost and by measuring ambient environmental conditions, and in which strain due to stress was evaluated from measurements of the physiological responses. The studies referred to manual transfer operations where the workers were paced by machines (Belding and Minard, 1969) and also to steelmill and aluminum smelting operations where the workers were self-paced (Minard, 1976; Stephenson, Colwell and Dinman, 1974). Consideration of the heat balance involved in the paced

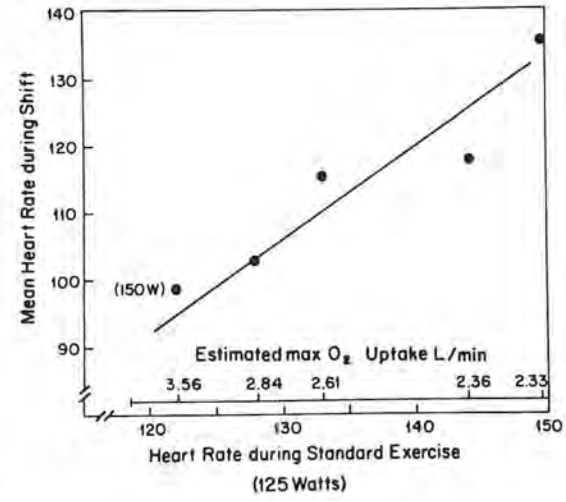

Figure 8. The correlation between mean heart rate during shift work and that during standard exercise on a bicycle ergometer for a second helper in the open hearth (steelmill). Adapted from Belding and Minard (1969) and Minard et al. (1971).

work indeed showed the need and possibilities of better control of the physical environment to reduce heat stress on hot summer days. When the workers were self-paced, however, the total heat load was reduced by lowering M and by shortening the period of exposure to heat.

An example of a self-paced operation is presented here as it was measured and recorded in a chemical plant. The job required tapping holes behind kilns set in line. This involved pushing a wheelbarrow and performing extensive intermittent arm work. On hot summer days, the workers paced themselves alternating tapping behind the kilns and then standing in a resting area next to large open windows where fans were blowing air into the plant. The pattern was repeated several times before the workers sought refuge in an air conditioned room. A time motion study was carried out on four workers at the time the physical environmental measurements were taken. The measurements showed the following:

Measurement	*Work site, tapping*	*Resting area, window*
Temperature, dry bulb, °C	55.5	33.5
Temperature, wet bulb, °C	33.6	26.5
Temperature, globe, °C	69.5	35
Air velocity (m/s)	1.96	5.2

The heat load (W/m^2) on a worker at both the working and resting sites were calculated from the simplified equations for heat exchange (see Appendix). Energy is expressed in W/m^2; $M + R + C = E_{req}$.

	Work site	*Resting area*
M	194	73
R	202	19
C	149	− 22
E_{req}	645	70
E_{max}	491	662
$E_{max} - E_{req}$	− 154	592

It is obvious that the total heat load required for dissipation (E_{req}) exceeded E_{max} by 154 W/m^2 at the working site. However, at the resting area with blowing air but a still high Ta it was possible to easily cool by evaporation: $E_{max} - E_{req} = 592$ W/m^2. The pattern of working and retreating to the window area had an average ratio of 0.7:1.

A weighted average of the E_{req} and E_{max} for the 0.7 ÷ 1 ratio will be $E_{req} = 260$ and $E_{max} = 502$ W/m^2 or a ratio $E_{req}/E_{max} = 0.54$. In the heat stress index (HSI) suggested by Belding and Hatch (1955), this is an acceptable work-heat exposure for acclimated workers, but supervision and attention must also be given to the drinking of water and to adequate resting. Resting and complete relief from the heat stress was possible in an air-conditioned room which was used by the workers for prolonged rest periods such as coffee breaks and lunch.

The physiological responses to work and heat exposure, as observed in the field, are described in the studies by Minard and his colleagues (Minard et al., 1971; Belding and Minard, 1969). A typical example is shown in Figure 9 for a second helper in the open hearth of a steel mill. It can be seen that during the 2-1/2 hr of recording, high heat levels coincided with high work levels. Observations through the whole shift showed that although M averaged about twice the resting value, it was at times as much as 7.5 times higher. This intermittent type of work, in which standing and sitting comprised about 30% of the total shift time and slow walking with light activities 20% of the time, revealed irregularly rising HR, which nevertheless progressively rose to a maximum of about 180 bpm. The typical example (Figure 9) shows that parallel with the average increase in HR, there was a progressive rise of Tc; both HR and Tc declined during recovery from the work and heat exposure.

The interrelation between the biophysical information and the physiological responses were also

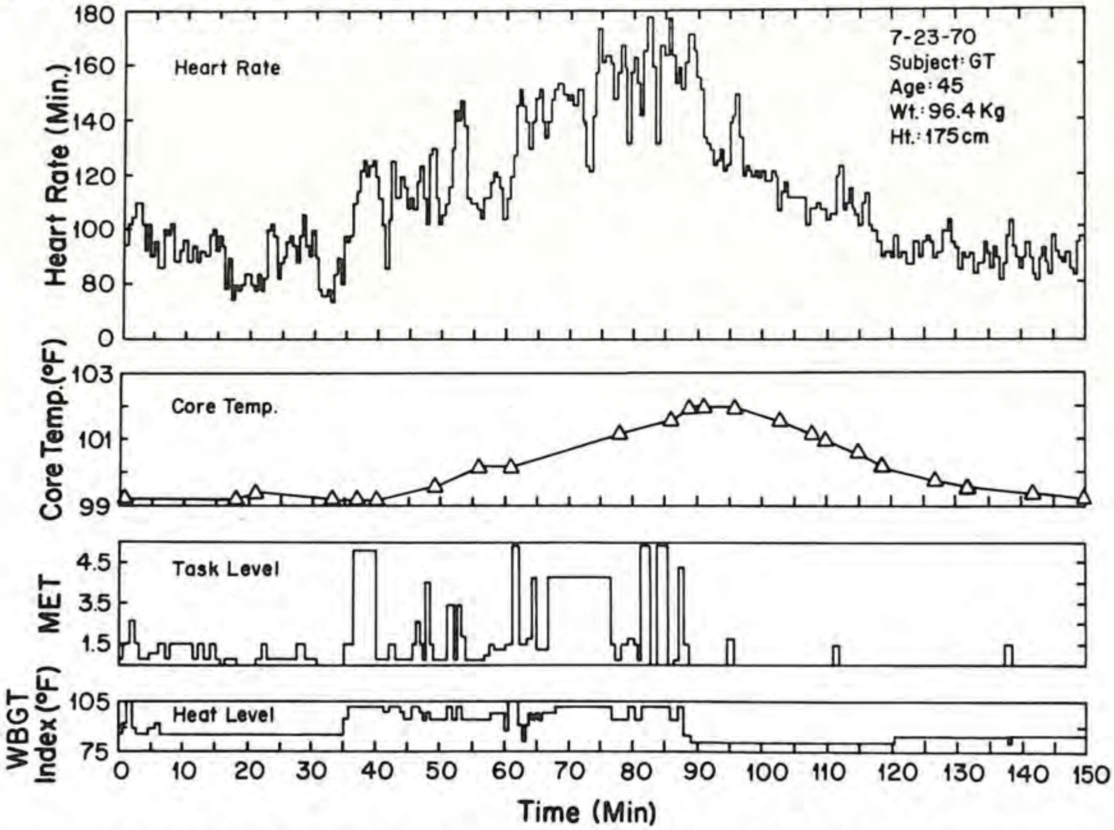

Figure 9. Time course of heart rate, core temperature, task and heat levels in a second helper during 150 minutes of work (after Minard 1976).

shown for aluminum smelting operation (Stephenson, Colwell, and Dinman, 1974). The authors emphasize the predictability of the physiological strain from the computed excessive heat (using the heat exchange equations as shown in the Appendix). Moreover, they showed that for all practical purposes, no physiological strain or clinical manifestation of it was found for the workers who controlled the thermal and work stresses by using an intermittent type of work that was self-paced. This was apparent in the low mean HR, whether averaged on a daily or weekly basis.

Designing Work-Rest Schedule

Physiologic Basis for Work-Rest Schedule

The practical solution to stresses due to muscular work and to heat is intermittent exposure. The physiological basis to the design of intermittent exposure calls for the expected responses to muscular work to be analyzed separately from those of heat exposure. The following is an example of our approach to quantify work-rest periods for dynamic muscular work under hot-dry and hot-humid ambient conditions. Although the derived values will differ somewhat when manual material handling is concerned, the principle should be the same.

To start, we developed a working hypothesis on the basis of our observations on HR changes during carrying and on the basis of reports by others on the physiological responses to work. Secondly, we tested our hypothesis in laboratory experiments.

The working hypothesis was based on the following assumptions:

1. Heart rate is linearly related to relative $\dot{V}_{O_2}$ such that at 33% $\dot{V}_{O_2}$ max. HR = 100 bpm and HR max is attained at $\dot{V}_{O_2}$ max. Although HR max and, to some extent, HR at submaximal work load fall with age, an average of a regression of 1 bpm increments for an increase of 1% $\dot{V}_{O_2}$ max of work is applicable. This gross approach can include men and women workers.

2. Work demanding 40% $\dot{V}_{O_2}$ max is endurable for an 8-hr shift assuming regular coffee and meal breaks (Åstrand, 1967).

3. Core body temperature equilibrates in proportion to % $\dot{V}_{O_2}$ max (Saltin and Hermansen, 1966), provided the ambiance is nonstressing; the applicable formula is given in Figure 1.

4. Heat-specific increments in HR, above the work-specific rate, can be considered as 1 bpm increment for rise of 1°C in hot-dry ambient conditions, and the increment in hot-humid conditions is relative to the ratio $E_{req}:E_{max}$ (see Appendix).

5. Workers are assumed to be fully heat acclimated.

Determining Work Periods

Assuming temperate, nonstressing ambient conditions, muscular work endurance to exhaustion is inversely related to % $\dot{V}_{O_2}$ max (Astrand and Rodahl, 1970, p. 292). Sound employment practice calls for a nonexhausting schedule. It can be inferred from a few published reports (Christensen et al., 1960; Åstrand et al., 1960; and Simonson, 1971) that when exercising at high work loads, work-rest cycles in which working periods of one-third the duration to exhaustion are adequate to maintain prolonged work. So, we have chosen to assume one-third the time to exhaustion as a safe limit for working periods. The following formula, which was based on information from the literature and the assumption mentioned above, was suggested for working time (T in minutes; see Figure 10):

$$T = \frac{40}{F_{max}} - 39$$

where,

$$F_{max} = \frac{\dot{V}_{O_2}}{\dot{V}_{O_2\,max}}.$$

Determining Rest Periods

The formula for adequate recovery time was derived from published reports concerning lactic acid formation in the muscles as a function of % $\dot{V}_{O_2}$ max and its rate of diffusion to the blood stream. (Karlsson, 1971; Borovetz and Weissman, 1972). Calculated rest time in minutes was found to increase exponentially with % $\dot{V}_{O_2}$ max:

$$\text{Log}\,T = 0.74 \times F_{max} + 0.74.$$

Figure 10 shows the working and resting time for a work range of 50% to 100% $\dot{V}_{O_2}$ max. The two lines intersect at about 67% $\dot{V}_{O_2}$ max and 20 min. Thus, a 20-min work period with a 20-min rest seems appropriate for such a work level under temperate ambient conditions. At about 80% $\dot{V}_{O_2}$ max, work time is 11 min and resting time is about 20 min. Figure 10 also provides the expected M at a given % $\dot{V}_{O_2}$ max for an average healthy man.

These two formulas assume nonstressing ambient conditions that will be used as the baseline for the stressful conditions.

Adding Heat Effects

The circulatory strain induced by excessive heat was treated in terms of % $\dot{V}_{O_2}$ max. As a general

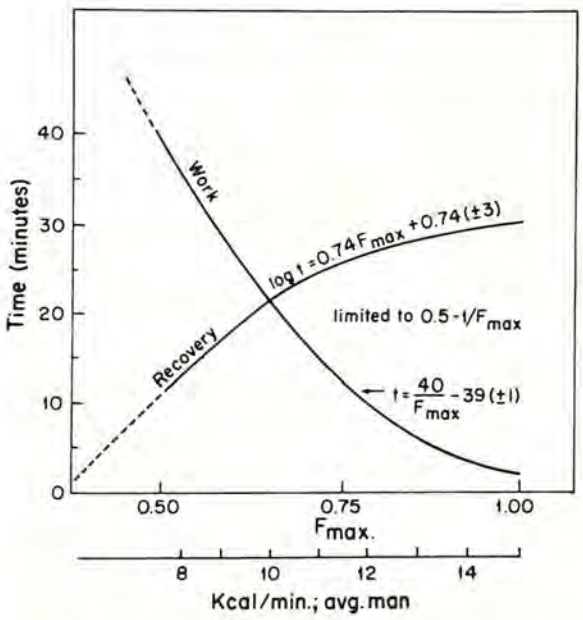

Figure 10. The suggested relationships between working time and recovery time and work load, given as fraction of maximal aerobic capacity (F_{max}) or the corresponding expected metabolic rate (kcal/min) for an average adult in his twenties.

rule, the expected heat-induced increments of 1 bpm in HR were equated to an increase of 1% $\dot{V}_{O_2}$ max. Or, using the rise of 1 bpm per 1°C increase in Ta (dry conditions) was considered as a rise of 1% $\dot{V}_{O_2}$ max. For example, at Ta of 35°C (10° above 25°C), the expected increment in HR was 10 bpm. The strain due to the heat at such time was taken to be equivalent to an increase of 10% $\dot{V}_{O_2}$ max for work under temperate conditions. Thus, if the actual work was at 30% $\dot{V}_{O_2}$ max, it was considered as work at 40% $\dot{V}_{O_2}$ max, for Ta 35°C. Support to this approach was found: 1. in the separation of the mechanical (motor) from the environmental (heat) factors in the increments of HR for experiments conducted by Vogt et al. (1973); and, 2. in the appearance of lactic acid (l.a.) in the blood for work at 75% $\dot{V}_{O_2}$ max under cold (Ta 9°C) and hot (Ta 43°C) ambient conditions (Fink et al., 1975). The authors reported not only higher HR, but also higher l.a. in the blood after work in the heat as compared with the cold Ta.

For humid ambiance with restricted evaporation (E_{max} less than M + R + C), it was assumed that HR, parallel with Tre, would continuously rise at rates of about 1 to 2 bpm every minute because of accumulated body heat. This, of course, depends on the difference between E_{max} and M+ R + C. However, for the design of our tests where about 20 min of work were involved, increments of 20 to 30 bpm above the work specific HR could be assumed (Stephenson et al., 1974). Increments of HR due to humid heat load were equated with increased M in the same way as for dry heat.

Testing Our Model

Economic consideration of industrial situations suggest equal work - rest periods to allow efficient employment. Therefore, equal cycles of work and rest for two workers or twice as much rest as work for three workers in rotating shifts were considered.

Based on the values shown in Figure 10 and assuming additional HR due to heat as equivalent to muscular work demands (in % $\dot{V}_{O_2}$ max), the following was scheduled:

> Forty percent $\dot{V}_{O_2}$ max with heat-induced increments in HR of 25 bpm above the expected HR was treated as equivalent to the strain expected from work performed at about 65% $\dot{V}_{O_2}$ max. Our formulas called for 20 min work and 20 min rest (see Figures 10 and 2). Sixty percent $\dot{V}_{O_2}$ max with the previously mentioned external heat stress was expected to increase the circulatory strain to that equivalent to 80% to 85% $\dot{V}_{O_2}$ max. Figure 10 shows that 85% $\dot{V}_{O_2}$ max calls for about 10 min of work and 20 min of rest (a pattern suitable for three workers on one job).

The following environmental conditions were chosen for the first trials: 1. warm, humid, Ta = Tr = 36°C, Tnwb = 32.5°C (natural wet bulb temperature, vapor pressure = 35 mmHg); 2. hot, dry, Ta = Tr = 50°C, Tnwb = 26°C (vapor pressure = 12 mmHg). Air movement was 1 m/sec for both ambient conditions. In one series, the work and rest were under the same conditions. In another, the rest was outside at Ta = 22°C, Tnwb = 18°C, and air movement 0.1 m/sec.

Each series was administered to four subjects. Since they were young, college age, relatively fit subjects, the M values at a given % $\dot{V}_{O_2}$ max was about the same for all of them. Such a homogeneous group made the analysis of the data simpler. The mean end values of HR and Tre for the 10-min work and 20-min rest periods are given in Figures 11a and 11b. The results of the 20-min work-rest cycle were similar to those for the 10-min work 20-min rest cycle. That is, they all showed that the design, if applicable in that body temperature and HR, levelled off, more or less, at acceptable levels for both hot-dry and hot-humid conditions.

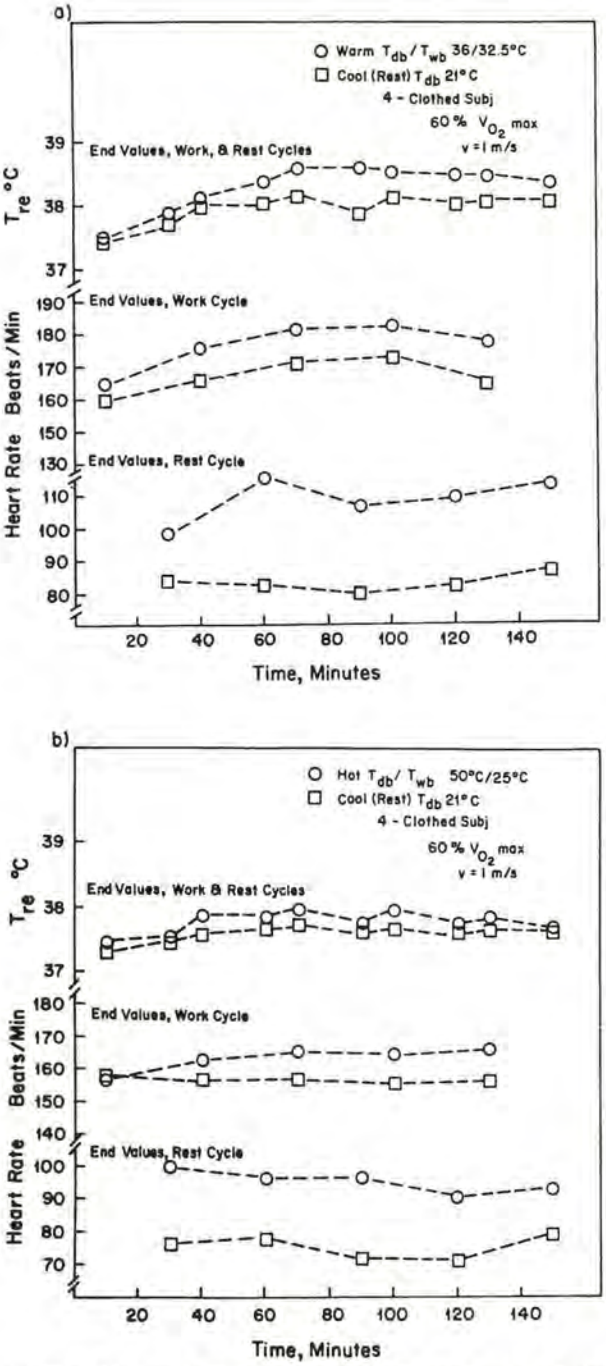

Figure 11. End values of heart rate and rectal temperature (Tre) for work and rest cycles (10 min and 20 min, respectively).

It can be concluded from our results that using the quantified physiological responses from the relative strain due to work and then adding on the expected standard strain value due to the heat is a workable method. However, it should be noted that this calls for either directly measuring $\dot{V}_{O_2}$ max or assuming it by age and sex. Tables for $\dot{V}_{O_2}$ max estimates by sex and age are available for rhythmical muscular contraction (American Heart Association, 1972). However, the values should be reduced by about 25% when manual material handling is concerned, because of the lower $\dot{V}_{O_2}$ max expected for manual handling tasks as compared with such rhythmical exercise as walking, running, or cycling (see Lind and Petrofsky in this book).

COLD STRESS

General Considerations

Cooling due to unfavorable conditions means the loss of metabolically produced heat (M) to the environment, by radiation (R), and by convection (C). The first protective mechanism against heat loss is the reduction of heat flow to the skin by constriction of the blood vessels. The reduced heat flow to the skin helps conserve the metabolic heat and lowers the skin temperature. The lower skin temperature results in a smaller skin-to-air temperature gradient, thus reducing the heat loss. Dermal vasoconstriction helps maintain a heat balance with comfortable sensation for men at rest to a Ta of about 27°C and to 21°C (dressed in ordinary business clothing). Actually, the latter condition was used to define the unit of insulation (clo; see Appendix). Further drop in the air temperature calls for additional protective mechanisms, beyond the increase in vasoconstriction. This calls for behavioral mechanism of which the most important is the donning of clothes. However, the amount of insulation by clothing depends on the work performed and the amount of metabolic heat produced.

The expected heat loss by R + C can be derived from the heat exchange equations (see Appendix), particularly for closed areas where mean radiant heat and air temperatures are similar. The coefficients for each avenue of heat exchange can be corrected according to the insulative clo values. In calculating R and C, the gradient between the air and mean skin temperatures can be roughly estimated from subjective sensation. Subjective, air temperature under 21°C is considered slightly cool, 10°C to 0°C is cool, 0° to -10°C is cold and under -10°C is considered very cold. This coincides with a parallel drop in mean skin temperature (Tsk). Thus, subjective feeling of comfort coincides with Tsk of 33°C; uncomfortably cold with 31°C; shivering cold with 30°C; extremely cold with 29°C and the tolerance limit with 25°C.

Core body temperature equilibrates at the level expected from % $\dot{V}_{O_2}$ max (Figure 1) at as low an air temperature as 10°C for seminude man and at even lower air temperatures for ordinarily dressed man.

Years ago Horvath and Golden (1947) reported that men dressed only in herringbone twill (1 to 2 clo) and working at levels requiring 1.2 l/min of O_2 at air temperature of -37.2°C, maintained a Tre of 0.8 to 1°C above the resting value that was expected from such work at temperate conditions.

Under cold and very cold ambient conditions, the work might provide insufficient metabolic heat. Excessive cooling to the extent that Tre drops below the resting value results in increased M, above that expected from the work load, by shivering, unless insulation is added.

Adequate metabolic rate that will compensate for environmental heat loss might not be practical in manual material handling because of the nature of the tasks of intermittent work under changing ambient conditions. Such circumstances require flexibility in adjustment of the clothing, since over-insulation might create hot microclimate and sweating during work.

Hand protection is an important aspect of manual material handling since they cool faster than the rest of the body (except the feet). Subjective scaling of discomfort in cooling the hands concurs with lower temperatures as compared with mean skin temperature. Thus, a hand skin temperature of 20°C is comparably cold; 15°C is extremely cold, and 4°C produces painful sensation. This same scaling agrees with 2° to 3°C higher skin temperatures for the feet.

When the microclimate is not warm because of inadequate clothing, work at submaximal levels elicit lower HR than the expected HR under temperature ambient conditions (Fink et al., 1975). The lower HR is a result of increased S.V. as was shown by Hanna et al. (1975) for work loads of 82 watts and 123 W on a bicycle under Ta of 4.5°C. The author attributed the increased S.V. to the excessive secretion of catechlamines. However, the increased renal return of blood due to vasoconstriction could also play a role in the increase of S.V.

The effect of cold on manual performance was reviewed by Provins and Clarke (1960). They cite studies, early in this century, that showed an increased number of accidents attributed to impaired dexterity by cold that might not be improved by mittens because of clumsiness. Cooled hands lose flexibility probably because of increased viscosity of the synovial fluid in the joints. There is a loss in strength that becomes more obvious when the forearm muscles also are cooled. Experimental findings showed that a man sitting in a cool room progressively decreased in grip strength with decrease in air temperature. Following immersion in cold water, two aspects of strength were reduced: maximal grip strength and endurance time at a given submaximal level; the critical muscle temperature was 27°C (Clarke and Hellon, 1959).

A study in Russia (Gorshkov and Kokhanova, 1966) of workers in a freezer (Ta = 19°C) who manually transferred ice cream boxes weighing 1 to 10 kg from a conveyor to storage area has shown that the latent period between thermal stimuli on the wrist and reaction time (pressing a key) was longer for these workers than for workers outside the freezer. However, the latent period did not increase as much as when the workers performed heavy work, as compared with light work. Since the workers were well dressed against the cold and had mittens on, this decreased latent period could be explained by better maintenance of body temperature due to the physical activity. This is supported by an earlier study by Wyndham and Wilson-Dickson (1951) that "confirmed the efficacy of physical work for promoting vasodilation in the hand through increase in body heat content." Therefore, manual material handling during cold exposure is better performed when work is not intermittent, core body temperature is not allowed to drop, and when the hands are kept warm for longer periods.

Practical Considerations

The relationship between the air temperature, metabolic rate and insulation requirements were studied for military operations (Newburgh, 1968). Charts and tables in this classic book clearly show that increased M requires less clothing insulation for a given Ta. For example, with a Ta of 2.2°C and work load at M of about 350 W, the required insulation is about 1.4 clo, which can be accomplished with one additional layer (a coat) above the ordinary working dress. However, sitting (M = 100 W) requires 4.5 clo worth of insulation, which can be accomplished with heavyweight wool underwear, jacket, pants, and heavy mittens.

The problem in manual material handling might, however, be the intermittent nature of the work and the required dexterity. Increased activity, which results in hotter microclimates under the clothing, can lead to sweating. A chill due to overcooling when activity stops is most likely to happen.

Therefore, the important factor becomes the behavioral aspect of donning and removing clothes (or, just hand covers) during the working and resting periods, or when moving between cold and warm environments. Since the efficiency of the clothing materials is relative to the air trapped in it, the thickness of the clothing is a good yardstick for its insulative power. For outdoor windy weather, however, a wind-resistant type of outer layer is helpful. Naturally, a light, easily adjustable type of clothing is best if a work-rest schedule is involved. There are synthetic types of fabric that could be well adjusted to work in the cold because of their low moisture permeability and reduced wickability. Moisture, whose convective power exceeds that of air, cannot replace air trapped in the clothing, and therefore, heat loss is reduced.

There is some safety margin to the adjusted insulation. A man can lose about 45 W/m^2 before discomfort prevails. Therefore, if insulation is inadequate and discomfort is sensed, rewarming might be advisable. If the cool air causes very slow heat loss, the deficit might exceed 45 W/m^2 (87 W for a whole man) before the discomfort can be sensed. In such cases, knowledge of the cooling capacity of the air might be helpful in scheduling the time of cold exposure.

Rewarming may be important if the work requires bare hands. Rewarming of the hands by use of mittens or other heating means should not be neglected. Rewarming of the whole body should be done cautiously. Usually, being in intermediate cool air will retain peripheral vasoconstriction but will allow spontaneous metabolic warming. This should precede entering a warm air environment in which cutaneous vasodilation might result in further cooling rather than warming of the blood pooled near the surface.

Guidelines for healthy working conditions and procedures are necessary for cold exposure. Relevant to this review is a guide that was published by the Royal Swedish Labor Protection Board (1971). The guide puts emphasis on the possible drafts that exist in refrigerators: air movement drafts and radiation drafts. Attention is given to check the air movement in refrigerators where cooling is not achieved by a refrigeration element. When the cooling system is a refrigeration element, a large temperature gradient between the area of the refrigerator element and the worker can cause radiation draft. The guidelines are, therefore, as follows:

- Guidelines to the design of a refrigerated room:
  - Air velocity at head height should be less than 0.15 m/sec.
  - Refrigerating element should have large enough surface area and be placed high enough to prevent "radiation draft."
  - Relative humidity should be maintained at less than 60%.
- Guidelines for workers in refrigerated rooms (Ta=16°C):
  - Avoid cooling of hands by insulating material to be handled.
  - Make sure to enter with suitable protective clothing and avoid prolonged standing or sitting.
  - Avoid perspiring before entering the room and ensure that your clothes are not damp.
  - Do not wear shoes with sponge-rubber soles because they collect moisture that might freeze you fast to the floor.
  - Upon coming out, brush off excessive frost and loosen your clothing.
  - Breathe through your nose. If you have a cold and can abstain from going into the cold rooms, certainly do so.

AIRBORNE MATERIALS

Airborne materials are atmospheric contamination due to primary pollutants emitted directly from auto exhausts or industrial sources and secondary pollutants arising from heat but mostly photochemical interaction in the air. These airborne materials can irritate the air passages and the lungs and disrupt the internal chemical processes of the body. Both effects could impair performance by interferring with the supporting systems for O_2 transfer.

The effect of some airborne materials on physical work was investigated under controlled laboratory conditions. These include such primary pollutants as carbon monoxide and lead and secondary pollutants such as ozone.

Carbon Monoxide

The effect of carbon monoxide (CO) on physical work was quantified in a series of studies, which showed its effect on the work capacity and the thermoregulatory processes. CO, by binding to hemoglobin (Hb), reduces its availability for O_2 transport; this, in turn, lowers $\dot{V}_{O_2}$ max. Thus, inhaling 225 ppm CO, which was supposed to maintain 18% saturation of Hb with CO (COHb), reduces $\dot{V}_{O_2}$ max by about 25% (Vogel et al., 1972). Since steady state HR and equilibrium level of Tc at submaximal work loads are inversely related to $\dot{V}_{O_2}$ max, such CO-reduced $\dot{V}_{O_2}$ max will result in higher HR and Tc than those observed under non-CO inhaled conditions. Indeed, when working at loads requiring about 1.5 lO_2/min (520 W), inhaling CO to the extent that $\dot{V}_{O_2}$ max dropped by 25% resulted in increments of 20 bpm in HR and rise of 0.2°C in Tc, above the values observed under air breathing ambient conditions (Nielsen, 1971). Moreover, exercise endurance to exhaustion was significantly lowered by inhalation of small amounts of 50 to 100 ppm CO for 1 hr, from which only 3% COHb was obtained (Drinkwater et al., 1974; Arnow and Cassidy, 1975). Exposure to heat stress and CO should have a synergistic effect in that both reduce $\dot{V}_{O_2}$ max. However, tests conducted under practically expected conditions of Ta

35°C and 50 ppm CO revealed minor changes (Drinkwater et al., 1974). The authors found that heat reduced $\dot{V}_{O_2}$ max by 4% as compared with the reduction of 3% due to 3% COHb saturation. Exposure to both heat and CO reduces $\dot{V}_{O_2}$ max insignificantly and should be considered minimal for all practical purposes.

Airborne CO is not the only cause of CO poisoning. Airborne chemicals such as dichloromethane (found in paint remover and varnish) was found to impair work (Stewart and Hake, 1976). With a yet unknown chemical process, the inhaled vapors containing the dichloromethane increased CO blood content and resulted in CO poisoning.

Lead

One recent study on the effect of airborne lead on muscular strength, which in a way is relevant to our topic, was carried out by Repko, et al. (1975) from NIOSH. They tested 316 workers involved in manufacturing batteries (lead-acid) and 112 workers who were not exposed to lead. Figure 12

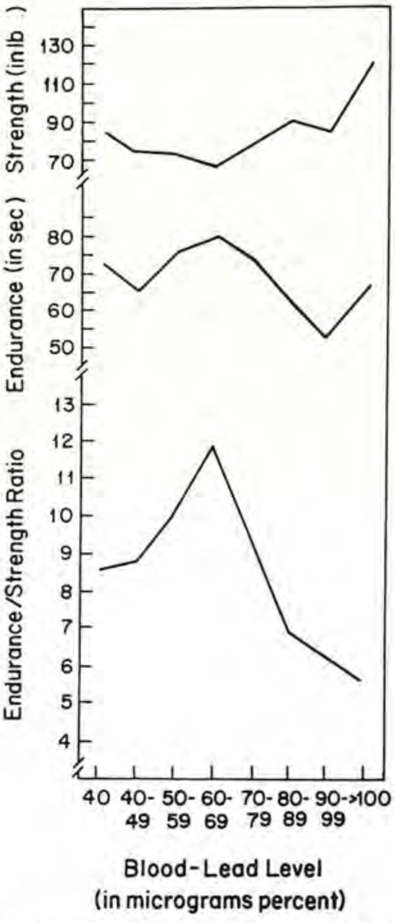

Figure 12. Strength, endurance, and endurance strength ratio as a function of blood lead levels (after Repko et al. 1975).

demonstrates the relationship between the lead content in the blood and two strength values: maximal grip strength and endurance at 50% maximal strength. It is interesting that maximal strength increased with the blood-lead content but endurance decreased. The authors attribute the paradoxial results to motivational aspects of the test. The weaker subjects tried harder at the maximal strength test from which the 50% max value was established. Therefore, at 50% max they had to overcome a relatively larger resistance that they could endure less.

Ozone

This irritant constricts the bronchioles. The constriction can be stronger than the bronchodilating effect of exercise. Indeed, it was found that airborne quantities of 0.75 to 0.9 ppm, which under certain circumstances are expected to pollute the air (sunshine and gas automobile emission), do affect breathing (Kagawa and Toyama, 1975). There is a resistance to breathing that, therefore, increases respiration frequency and decreases tidal volume in proportion to the ozone inhaled (Folinsbee, et al., 1975). However, these changes did not seem to affect the rate of ventilation and O_2 uptake for the submaximal work tested in these experiments.

APPENDIX

The calculation of the heat load due to (M) and the exchange of heat by radiation (R), convection (C), and the ambient capacity for skin evaporation (E_{max}) are given below. Recent summary of the approaches taken to compute the heat exchange can be found in Hardy, et al. (1970) and Monteith and Mount (1974).

Metabolic rate (M) is derived from measured O_2 uptake. Since most of the energy appears as heat, the conversion using the factor of 5.8 W per 1 l of O_2 consumed is applicable for all practical purposes.

The practical formulas for a nude person, expressing the energy in W/m^2 and temperature in °C could be summarized:

$$R = 5\,(Tr - \overline{T}sk)$$
$$C = 8.4 \cdot v^{0.6}\,(Ta - \overline{T}sk)$$
$$E_{max} = 18.5 \cdot v^{0.6}\,(Psk - Pwa)$$

where

Tr is the mean radiant temperature; $\overline{T}$sk means skin temperature; v is air movement in m/s, Ta is air temperature (dry bulb), Psk is the saturated skin vapor pressure, and Pwa the ambient water vapor pressure in torr (mmHg).

Tr can be derived from the temperature of a 15-cm black globe (Tg) as suggested by Haines and

Hatch (1952): $Tr = Tg + 1.8 \cdot v^{0.5}(Tg - Ta)$. $\overline{T}sk$ can be assumed 35°C under hot ambient conditions and 33, or less, (see text) for comfortable or cold ambient conditions; Psk for the assumed $\overline{T}sk$ of 35°C is 42 torr.

Applicable formulas for industrial situations call for correction of the heat exchange because of the clothing. Belding. et al. (1960) found empirically that the coefficient for R, C, and E_{max} can be reduced by the factor 0.7, for an ordinarily dressed worker (long sleeves shirt, and trousers). This correction is in agreement with the general correction factors for clothing suggested by Nishi and Gagge (1970), on the basis of the clo values of the clothing.

The different insulation values of clothing are more applicable to cold than to heat. The clo unit was empirically defined as the insulation necessary to maintain comfort and mean $\overline{T}sk$ of 33°C in a room at 21°C with air movement of less than 10 cm/sec and relative humidity less than 50% for a sitting man (M = 58 W/m^2).

Under cold ambient conditions, unless overclothed or hyperactive, heat loss by evaporation is expected to be minimal. This minimal evaporation (E) is due to insensible water diffusion through the skin and mostly through the lungs, and a negligible loss of heat by warming the cold inhaled air. Heat loss through the lungs is linearly related to the ventilatory rate which, in turn, is almost linearly related to the metabolic level (M). A good estimate of the heat loss is 25% of M. Therefore, the heat balance equation can be described as $M - E = R + C$, or because $E = 0.25$ M, the balance is $0.75 M = R + C$.

The heat exchange balance is also related to the cooling rate, which according to Newton's law is proportional to the temperature gradient between the skin and the air but is inversely related to the insulation. The above described conditions for the definition of the insulation unit was for a man in ordinary business clothing in the United States. Thus, the heat balance equation becomes:

$$0.75\ M = K\frac{\overline{T}sk - Ta}{Insulation}$$

where

K = the coefficient applicable to M in W/h, and T in °C is 6.2 W/m^2 °C.

Using the conditions described above:

$$Insulation = \frac{6.2\ (33\text{-}21)}{0.75 \cdot 58} = 1.7$$

0.7 is the insulation value for the air layer, and 1 clo is that for the clothing. Since the clo value of air drops with an increase in air movement, the clo value of the clothing should be increased in proportion to the prevailing air speed.

Another expression for the clo unit is the insulation that will allow the passage of 1 kcal per m^2 per hour for a temperature gradient of 0.18°C between the two surfaces.

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CHAPTER 4. SUMMARY

In the M.M. Ayoub et al. paper we see the interesting situation of too many relevant data being available to predict outcomes. Many of the human physical attributes are correlated so that choosing the "best" one or ones may be a matter of defining "best" in a statistical sense of minimizing predictive error. The relatively new technique of Ridge Analysis may be a way out of the traditional shaky assumptions of multiple regression analysis and its habit of coming up with predictive equations that make no logical or physical sense.

When the factors in the final equation are examined, they consist of box length, lift frequency, height of lift, and two measures of strength. Interestingly, for a paper on individual differences, sex is not a factor, it being subsumed by the strength parameters. The model brings in biomechanical parameters and physiological parameters (frequency of lift) to predict psychophysical data.

In contrast, Shealy finds many ill-defined concepts and less-than-logical research paradigms in his survey of risk taking. The intersection of the set of risk taking studies and the set of manual materials handling studies appears to be empty. Even studies of risk taking in skilled performance are few, with Shealy's own representing the bulk of the reliable research. And yet, when accidents do happen and productivity does suffer, management and supervision have an almost reflex action of judging the worker to be at fault. This is usually followed with a poster and pep-talk campaign aimed at changing the hearts and minds of the work force to produce a less risky attitude towards work. Any reader who still has the comforting belief that this approach must have proven effective somewhere should read Hale and Hale's (1972) somber review of the industrial accident literature. The human factors/ergonomics tradition has stemmed from World War II observations that labeling accidents as "pilot error" did little to reduce their number or severity. They, therefore, deduced that task and environment are all-important and the human operator is an unchangeable part of the system. The more recent view (e.g., Singleton, 1974) does not close its eyes to the fact that some operators may be unsuited to the job. Shealy points a clear finger at the need for research in risk taking in manual materials handling as a common sense approach that has been totally neglected. His contribution would make a good starting point for such research.

Even so mundane a subject as container design can have interesting modeling overtones as M.A. Ayoub shows. The problem is not just lifting boxes; it is the entire range of handling aids (or hindrances) devised by engineers to protect the product rather than the product plus the operator. The important principles should now be obvious; design for minimum strength requirements and minimum spinal stress. To complement this paper, Morowski and Liuzzo, in an unpublished review at SUNY Buffalo, showed a research need in the area of handle design for manual materials handling. There are many recommendations on handle size (unsupported by data) but little on handle placement or on texture and shape details. The work on hand tools may well not be applicable to manual handling aids. Clearly, the most obvious man/machine interface of all has not yet been given the research it requires for practical recommendations to be made.

Frequency, duration, and pace are not usually considered as independent, but Burse suggests that task frequency may limit materials handling performance in a different way from duration of each cycle of the task. His review of a large number of studies shows the similarities in the numerical results from widely different populations. The exception is the Jorgensen and Poulsen study that quotes much higher maximum weights than are usual. Work-rest scheduling for single sustained contractions and dynamic repetitive work, as presented by Rohmert, is rarely applied in industrial manual tasks. Typical of industry's approach has been the table of rest allowances, based on little hard evidence and much common sense. Unfortunately, these allowances are often expressed as a percentage rather than specifying the specific work-rest schedules that would minimize physiological strain on the operator. For thermo-neutral environments, the accepted limits appear to be a heart rate of less than 115 beats/minute and a workload over the working day that averages to less than 40% or 50% of maximum oxygen uptake.

Extending this concept to environments with thermal stress is the subject of Kamon's paper. With thermal stress affecting the heart rate in addition to the metabolic stress, all the thermal factors affecting safety and performance need to be considered. The equations for radiative, convective, conductive, and evaporative heat transfer can be particularly complex for human beings (e.g., Berenson and Robertson, 1973). Kamon's methods, as well as those of Givoni and Goldman (1973), seek to abstract the essential parameters, to describe the complexity of clothing in simple numbers, and hence, to achieve a reasonable level of prediction despite industrial, rather than laboratory, measurements of environment.

Is it possible, given the large effects shown in this chapter, to arrive at a checklist of factors to be taken into account in task design? Because of the interrelationship between the variables, a checklist is of less use than some more structured cause-and-effect diagram in which task demands and worker capabilities can be organized. Figure 1, based on material presented in the chap-

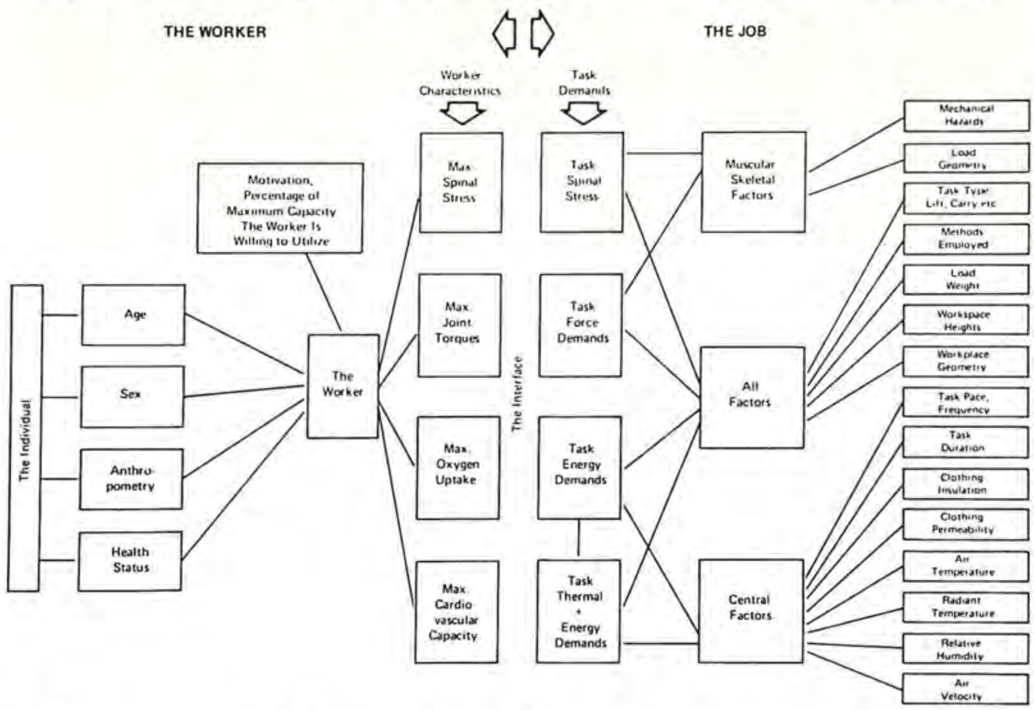

Figure 1. Interrelationships between manual materials handling variables and the worker.

ters so far, illustrates one way of structuring the problem. It attempts to simplify by including only major known effects; for example, the thermal environment presumably affects muscular endurance but this is omitted. Again, it simplifies by omitting the conditioning effect of work: task demands can change the worker, for example, by muscular training or thermal acclimitization. In this sense, it represents a final equilibrium condition after transients such as initial training have passed.

Using this structure leaves researchers with three tasks:

1. Developing methods to measure or predict the capability values for an individual.
2. Developing methods to predict task demands from easily measured physical parameters of task and environment.
3. Validating the relationships between individual capability values, task demands, and health status measures such as injuries, etc.

All three are well underway, as evidenced by the papers in this volume. The next step is to see how far we can go *now* using currently available knowledge to intervene on the side of safety. Hence, Chapter 5.

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CHAPTER 5

IMPLEMENTING MANUAL MATERIALS HANDLING RESEARCH

INTRODUCTION

From theory and from known effects will come the solutions to manual materials handling problems. Although research must go on to develop better countermeasures, the real test is to apply present, imperfect, knowledge to prevent injuries that happen at the frightening rate mentioned in earlier chapters. Every call for more data, every rethink of recommendations means potentially preventable injuries. If inaction is unappealing, then premature recommendations are equally abhorrent. Training in inappropriate methods; standards so loose as to promote false security or so tight as to be held in contempt by manager and worker; ill-considered mechanization schemes which further contribute to decline in both physical fitness and national energy reserves — all are possible.

The nontechnical literature on manual materials handling seems to emphasize training in methods as an intervention strategy. There have been advocates of numerous methods — each new and each apparently working for its inventor. The effectiveness of this training emphasis is largely unsupported by valid data; even the laboratory data showing the superiority of particular lifting methods is less emphatic than it once appeared. The other problem with training is that people tend to forget their training under stress or distraction and revert to an earlier method. This effect can be minimized if the workplace is designed so that the best method is the most obvious or natural method.

Training may have its faults, but nobody doubts that it will remain one arm of any concerted strategy to reduce injury. What others are possible? An eloquent plea for selection is made by the Herrin paper in this volume. Within the range of most other abilities and with the correlation between strength and safety now being proven, it is obvious that the worker must be fitted to the job as well as the job fitted to the worker. Fitting the job to the worker is the traditional province of ergonomics/human factors found in most North American industry in the industrial engineering department. But safety managers are also involved in this endeavor, although usually from the different perspective of injury control and implementation of standards.

Whichever method is chosen, the prime requisite is the same — a detailed analysis of the task. A selection scheme needs to measure the skills required so that applicants can be tested for the appropriate human abilities and these abilities can be used in placement decisions. Modern training schemes such as those described by Salvendy and Seymour (1973) need skills analysis. Job redesign from an industrial engineering perspective regards some form of task analysis as central. Indeed, one such study by Garg (1976) has attempted this for manual materials handling. Safety and accident control need predictors for what Swain (1973) calls "accident prone tasks"; these predictors must ultimately come from an identification of the job-element associated with the accident or injury.

Traditionally, the safety approach has relied on a study of how the system has malfunctioned, whereas industrial engineering (and a good portion of the research community) has concentrated on defining and implementing some "best" way to perform each cycle of the task correctly. Recent years have seen a synthesis of both these approaches, as evidenced in all the papers in this chapter.

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TRAINING IN MANUAL HANDLING AND LIFTING

B. T. Davies

Training in manual handling and lifting has made an upsurge in the United Kingdom in the last 25 years. This was triggered to some extent by the work of McClurg Anderson (1951) and furthered by the Royal Society for the Prevention of Accidents, The British Safety Council, and The Chartered Society of Physiotherapy. Research into certain aspects of lifting, both physiological and psychological, has subsequently been carried out by such as Davis and Troup (1964), Snook and Irvine (1966), and Whitney (1958), although these are a progression on the much earlier work by Cathcart et al. (1923), Crowden (1932), and others.

We know that, despite instruction in lifting and handling in many parts of the world, the accident figures show virtually no decrease. As someone who has advocated this training, these accident figures have caused me some concern, and like others, especially Brown (1971), I have tried to find reasons for this apparent failure.

When we look for reasons why figures for back injuries due to lifting and handling remain fairly high and unchanging, we could well consider the following points:

1. Much teaching has advocated a knees bent/back straight method of lifting that, in the opinion of those who recommend the kinetic method, predisposes to injury because of the unstable starting position.

2. The number of workers who receive any instruction, when compared with the working population from which accident figures are quoted, would appear to be minute.

3. The number of workers who receive what could be considered first-class instruction, i.e., the kinetic method with regular follow-up from qualified instructors, is even smaller.

4. Nowadays workers may tend to take time off for injuries because of the improved social environment. Quite often there is no financial inducement to return to work quickly.

5. Often, too, there is a possibility of financial recompense if responsibility for the accident can be attributed to the employer, although there is no firm evidence of a compensation syndrome.

We can consider there is a choice among three methods of lifting (see Figures 1, 2, and 3):

Figure 1.
Straight back, bent knees lift.

Figure 2.
Free style or "bend over" lift.

Figure 3.
The kinetic lift.

1. The straight back/bent knees method that, until recently, was advocated by the National Safety Council, the U.S Department of Labor, and Grandjean (1969).

2. The free style method, which is the common way of lifting, with knees straight or slightly bent and a rounded back — sometimes called the "bend-over lift."

3. The kinetic method, described in more detail later, that consists essentially of a straight back and a stable base from which to lift.

STRAIGHT-BACK, BENT-KNEES METHOD

With this method, the position of the feet is not specified. It is, however, apparent from Grandjean and the U.S. Department of Labor that the position can vary from close together (and parallel) to wide apart (and parallel). Lifting from this position, because of the small base (especially in the sagittal plane), leads to an unstable starting position for a lift. Subjects become more concerned with keeping their balance than performing the lift. The almost full flexion of hips and knees needed to lift an object from the floor causes a raising of the heels so that only the front part of the foot is in contact with the floor. This makes the base smaller and the position even more unstable than the original starting position.

THE FREE STYLE OR BEND-OVER LIFT

The free-style lift is the most common way of lifting and is the method used by people who have received no instruction in lifting.

Some may argue that this is the natural way of lifting, and indeed, it has been shown that physiologically it is more economical than the generally advocated knees-bent lift (or kinetic lift). Das (1951) has, however, shown that there is a changeover point at about 25.4 kg (56 lb) when it becomes physiologically more economical to lift with the knees bent. It can be argued that a slight increase in energy expenditure is worthwhile in a lifting task if the "improved" method provides more stability and reduces the load on the back muscles and intervertebral discs.

THE KINETIC LIFT

The kinetic lift incorporates, what is considered by many to be, the main factors in avoiding injury — not just to the lower back but also to most parts of the body. It incorporates six main features:

- back straight,
- chin in,
- good grip,
- foot positions,
- arms close to body, and
- use of body weight.

It is believed that the application of these principles, which are now taught by most of the safety organizations in Great Britain and have the tacit support of the medical profession, can prevent many accidents in the lifting and handling of material.

TRAINING

Brown (1971) reported that there is no evidence to suggest that the straight back/bent knee method is advantageous. This may well be true, but this is not the method advocated, and he goes on to recommend that workers adopt a "free style" or natural lift.

This raises the whole question of why we consider training in lifting and handling. It would seem that the reason for training is that the "natural" way of lifting has led to an unacceptable number of back injuries. (Yet this method is still taught; Ring, 1973.) Can we then condone a return to this method of lifting? We have to accept that few, if any, in-depth acceptable scientific studies have been made in this area of the effectiveness of lifting and handling training schemes. Much of what is stated is just a subjective assessment of the situation, with the occasional study confirming this subjective assessment and stating that training schemes devised and carried out by well-qualified people, i.e., physiotherapists and medical officers with backup of a safety poster campaign, can be effective.

I believe the following three lifting and handling training programs show that these programs can be effective if carefully designed and properly carried out. None of the authors would claim that these figures are scientifically validated; however, until we have in-depth studies, these are probably the best figures available.

Reports from John Player & Sons (Haynes, 1976), cigarette manufacturers of Nottingham, England, show that, following a carefully planned program by the physiotherapists and the safety committee, back accidents were reduced from 27% to 19%. This safety campaign was particularly instructive as it included, after the physical instruction, the use of posters (Figure 4) in the currently acceptable fashion, i.e., changed at regular short intervals. I expect their impact is obvious.

A personal communication from Davis (1976) indicated that injuries caused during the handling of

Figure 4. Safety posters for training in manual handling and lifting.

underground pneumatic pit props were reduced by some 50% following a specific campaign of instruction in the safer handling of the offending item. An investigation of the techniques of handling the pit props is reported by Davis and Troup (1966).

The last communication comes from another large organization, Standard Telephones and Cables Ltd. (Blow, 1976). Here, following a disturbing increase in the number of back injuries and the number of working man hours lost, Dr. R. Blow, the Senior Medical Officer, initiated a very carefully planned campaign at a factory where some 500 men were employed in manual work.

Following the instruction, Dr. Blow analyzed the safety statistics each month and stated "I know of no other event which might have produced this reversal apart from the instruction courses last year. The national figures continue to rise" (Table 1). This report is interesting inasmuch as it gives a gross cost-benefit analysis of the instruction course, showing a saving of approximately $10,500 (£5,250).

Table 1. Accident man hours lost Jan-Aug.

Year	*Handling accidents*	*Change*
1970	1837	
1971	1378	− 459
1972	2907	+1529
1973	4815	+1908
	Training Introduced	
1974	2687	−2128

A SPECIMEN TRAINING PROGRAM

The suggested program that follows is based upon a program described by Davies (1961), with some modifications, and may be considered as a general training program as distinct from a specific program aimed at one particular maneuver responsible for a high incidence of back injuries.

The following equipment is needed:

- 1 - 40-gal drum weighing about 360 lb
- 4 - wooden boxes (made of a special wood, Jelutong, to avoid splinters) with handles; 3 weighing 56 lb and 1 weighing 76 lb
- 4 - wooden boxes without handles; 3 weighing 56 lb and 1 weighing 112 lb
- 1 - sack-truck

To augment this standard list of equipment, other items known to cause difficulty in handling in the particular factory can be added.

The demonstrator is suitably dressed in overalls, safety shoes, and gloves. A short talk is given on the reason for such a program and the benefits to be gained. A simple explanation of the likely causation of hernia is given, based upon the work of Professor P. R. Davis (1959). The technique of moving the oil drum is shown first. Skillful and apparently easy movement of such a heavy awkward weight immediately commands respect, since the demonstrator is of average physique, and his handling of such a weight by brute force would be almost impossible. The class is shown the common faults in handling oil drums, i.e., finger grip, bend-over lift, poor foot position, etc. This advocated method (kinetic method) of tackling heavy weights can also be used for moving beer barrels, gas or electric cookers, sideboards, large heavy boxes, etc.

The class is then shown the "usual" way of lifting boxes (or any other weight) from the floor, and the extra strain and difficulty is illustrated by comparing this usual position with the one advocated where the foot is alongside the object, pointing in the direction of the movement and the other foot is behind the object to be lifted. The easier method of lifting and carrying a box without handles is shown, and the need for a good palmar grip is illustrated. The danger of the generally accepted "full-knees" bend (with very small base) is shown. Subjects are invited to push over the demonstrator who has adopted this position. The position is so insecure that this can be done by a gentle push with the little finger.

Participants must initially consider all lifts, until avoidance of twisting movements is encouraged. It is our experience that by far the most common cause of injured backs is an unexpected jerk in a flexed rotated position. Pointing the foot in the direction of movement before a lift eliminates the need to rotate the spine.

The class is shown how to up-end a sack, and two people are shown how to lift and carry the loaded sack. The common method of two people lifting a weight is burlesqued to emphasize how important it is to lift on a given command by one of the workers. The sack is then lifted to a suitable height (the imaginary tailboard of a truck), and the easier method of taking the sack from the truck is shown, i.e., leading foot pointing in direction of movement, good palmar grip on ears of sack, straight back, knees slightly bent, with a slightly upward initial movement.

The danger of wheeling a sack-truck with only one hand on the handle is demonstrated by showing what happens when one wheel hits a small obstruction (e.g.) a pebble, or piece of metal. The "free" handle swings violently into the groin, and the worker's own momentum gives it added impact.

And finally, the class is reminded that the 1939-1945 British war casualties, including deaths, were 10,667 per month. In the same period, casualties in British factories were 22,109 per month. Monthly figures for the United States were 24,896 for Armed Forces and 106,747 for industry (ILO, 1949).

What we are all involved in is an attempt to reduce these grossly insulting figures.

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FUNCTIONS OF INDUSTRIAL ENGINEERING IN MANUAL MATERIAL HANDLING SAFETY

S. K. Adams

THE SYSTEMS APPROACH TO DEVELOPING RECOMMENDED CRITERIA

The development of a systematic organization and priority ranking of research efforts by the National Institute for Occupational Safety and Health (NIOSH) in 1974 was an important step in organizing and coordinating research efforts on the problem of reducing or eliminating the causes of manual material handling injuries. Industrial needs can best be served through the coordination of research in a number of different areas including use of biomechanical, physiological, and psychological models to study particular problems. It is likely that a comprehensive research effort supported by industry and government will lead to the development of specific standards and criteria with respect to such areas as the human engineering of packaging (handles, instructions, noting center of gravity, designating the need for team handling, etc.). It is also likely that guidelines will emerge for selecting and training workers based on injury susceptibility (Adams, 1973). Ultimately a comprehensive management information system may be available for integrating numerous surveys and applied research programs.

A few comprehensive applied industrial research programs are already well underway, notably those being conducted through a cooperative effort between the Department of Industrial and Operations Engineering at the University of Michigan and the Western Electric Company (Chaffin and Park, 1973). Regardless of the technical discoveries and sophisticated methodologies developed in such applied programs, the results will have to be usable by the vast majority of companies and managers who have had no formal training in human factors engineering. In the author's opinion, this is where the most severe difficulties arise.

The application of human factors engineering to manual material handling can be handled effectively in large companies employing industrial engineers who are able to utilize current research developments. Industrial engineering has always had to cope with the problem of designing jobs for people. Recently developed techniques for investigating human performance and for evaluating occupational stress and injury have made it possible to design against predictable hazards arising from the operator-task-performance-environment system (Herrin, Chaffin, and Mach, 1974). Applying these techniques significantly increases the level and quantity of technology used in designing what are usually considered very ordinary jobs. Regulations affecting manual handling will affect "fundamental industrial engineering technology" in that they may make traditional methods of evaluating work and selecting workers obsolete (Faulkner, 1975a).

Such changes will probably affect small businesses more significantly than large ones that regularly employ advanced techniques in solving their operating problems. The specification of procedures used in selecting and training workers and a method to be used in the physical evaluation of jobs could be expressed in the form of a general standard. At present, it appears that the initial form of such a standard would be a technical guide and not a set of exact quantitative rules. Recent developments in biomechanics and psychophysics suggest that a three-zone standard (no restrictions, screening required, prohibited activity) can be stated quantitatively as a general guideline subject to refinement as more data are gathered. Standards should be beneficial to small companies unable to afford a research program by letting them participate in the results of studies conducted by larger companies or by the government. The development of standards should actively involve as many major corporations as possible to ensure practicality and economy in application.

PLANT MANAGEMENT OF MANUAL MATERIAL HANDLING

Departments and Their Functions

While working as a consultant for a large insurance company on the problem of developing a systematic approach to material handling safety (both manual and mechanized), the author was able to observe safety engineering and management practices within 14 manufacturing and distributing firms handling many types of products. Plant employment varied from under 100 to over 5000, thus providing examples of many different scales of operation. It was possible to spend only a few days with each company. During this time several departments and individuals were interviewed, plant inspections were made during operations, and material handling accident statistics were investigated. (Only data on manual handling will be discussed in this paper.) The individuals and/or departments contacted included:

- safety director and safety personnel,
- medical personnel (usually the plant nurse),
- industrial engineers and, generally, the director of industrial engineering,
- plant engineers or equipment design engineers, and
- management (foreman and shop superintendents) and, occasionally, general plant management.

The author found that he was able to communicate effectively with most of these individuals on matters involving industrial operations, safety, human factors engineering (to some extent), training, management policies, material handling systems and hardware, production economics, and management attitudes. Of all these departments, safety departments and, in particular, safety directors were most cooperative. They were most willing to admit that problems existed and were most willing to discuss these problems and to receive suggestions. Safety personnel were also found to have broad general knowledge of plant operations. They were generally respected by the work force and were not suspected of having other motives such as work measurement. The safety department was nearly always the first department contacted in making a company study.

Industrial medical personnel were also helpful in retrieving accident files and statistics and in offering suggestions relative to the causes of accidents. Medical personnel often hear what employees will not discuss with their supervisors.

Industrial engineering and other engineering departments (usually plant engineering, which is responsible for the design of material handling equipment) were contacted whenever possible. *Industrial engineering had the greatest potential impact on manual material handling safety of any single staff organization.* This is true for two reasons:

- It is the only group of individuals with the responsibility of studying shop operations in detail.
- It is the only group responsible for designing work methods and standards.

In theory, industrial engineering departments are in an ideal position to study shop operations for the purpose of redesigning jobs so that hazards are reduced or eliminated. In practice, industrial engineers are almost totally involved with work measurement, standard data, job descriptions, and cost control. From the author's observations, many work methods were derived from trade practices and past experience. Creative work design in the sense of human factors engineering was rarely observed. There was also a reluctance to admit that hazards were present on some jobs. "Hazardous methods would not be approved. Therefore, they do not exist." Limitations in lifting are usually established arbitrarily and in terms of weight only. Typical maximum limits for an individual male lift ranged from 22.7 to 38.6 kg (50 to 80 lb). Heavy objects were often bulky in that their center of gravity was some distance from the worker's body.

With respect to unsafe manual handling practices in the workplace, industrial engineers were placed in an awkward position. If the practices were part of the approved standard method, then method design was improper. As pointed out, this "cannot be." If this premise is accepted, then the worker is using an unapproved nonstandard method, thereby suggesting insufficient or ineffective auditing of methods and standards, another unwelcome problem. In the judgement of the author, it was for reasons such as these plus limitations in time to study manual handling safety that caused the industrial engineering department to leave matters concerning safety to the safety department. It did not appear that industrial engineers interacted significantly with individuals other than foremen and supervisors in reaching decisions regarding work methods, conditions, or standards. It also did not appear that human factors engineering concepts were used significantly in designing manual material handling methods.

Another important aspect of the manual material handling problem concerns the fragmentation of the overall work design system analysis into several separate and often poorly coordinated efforts such as: methods design, selection, training, development of standards, and hazard control. These activities need either to be integrated into a single work system design function or be closely coordinated and managed in a manner reflecting good ergonomic practice.

It is possible that the procedures used in this survey biased the results obtained. Since counterbalancing is impractical in this situation, the procedures used are listed below as a reference for individuals involved in future studies of this kind. Contacts and tours were made in the following order:

1. Contact and discussion with the safety department were made to define key problem areas and to become familiar with overall plant operations.

2. A tour of plant facilities was conducted on which the author was accompanied by the safety director or, in some cases, by an industrial engineer.

3. Conditions and findings were discussed with the safety director.

4. Discussions were held with plant medical personnel. Medical and accident data on recent cases were also reviewed.

5. Discussions were held with the department of industrial engineering and with various managers.

6. A final review of findings was held with the safety director.

Typical Problems

Some typical problems encountered in manual material handling operations included:

1. A frequent lack of relationships between job safety analysis and work methods design.

2. Inadequate feedback from the medical department to industrial engineering with respect to the specific event associated with injury in manual handling.

3. Lack of adequately planned procedures for handling variable stock such as scrap sheet metal or mixed castings.

4. Lack of adequately planned procedures for handling reject stock and assemblies.

5. Lack of standards and limitations of manual handling that incorporate factors other than weight of object.

6. Cramped work spaces that do not permit natural movement of the body while handling.

7. Problems in handling material that becomes tangled or tends to stick together causing recoil and unpredictable jerky material movement.

8. The need to hold one end of a bulky object while the other end is being processed as in end welding.

9. Lack of understanding or training in the area of handling and guiding suspended loads. Although most of the work in such an operation is mechanized, the human operator exerts relatively small but important forces in guiding and positioning. He is often in danger because of imbalance of larger forces such as occur in swinging, turning, initial lifting, and fitting into confined areas or on limited contact support frames.

10. Overcrowded or cluttered work areas.

11. A lack of consideration of body position and its effect in creating large moments when load centers of gravity are located too far from the back or shoulders.

INDUSTRIAL ENGINEERING — ITS ACTUAL AND POTENTIAL ROLES

Current recognition and utilization of industrial engineering have placed the industrial engineer in an ideal situation to improve safety by removing unsafe acts, poor conditions, and high effort requirements from the manual handling systems. Such a task is far too vast and too complicated to be undertaken by the safety department alone. In a typical plant employing 2,000 or 3,000 people, one typically finds only 2 or 3 individuals employed full time in occupational safety (extending this to medical personnel, perhaps another 1 or 2), but 10 to 15 or more employed in industrial engineering. Apparently the potential exists, in most industrial operations, to carry out a very practical and economically feasible program in manual handling safety. Unfortunately, industrial engineering seldom recognizes the significance of manual handling problems in designing processes, methods, and standards. Elimination of these hazards is not often included as a major design objective. For example, in designing a process, consideration of the handling of reject units or substandard material is seldom made. The suggestion of a second roller conveyor to handle rejects of a heavy or bulky item may appear to imply the anticipation of a large number of rejects and, therefore, may not be included among recommendations for approval by management. In such cases, it may be necessary to point out that the purpose of the conveyor is to protect the operator.

Before discussing the actual and potential roles of industrial engineering, it is necessary to define the typical professional nature of industrial engineers found in manufacturing. Many individuals performing within the industrial engineering function are not industrial engineers by formal training. Some have degrees in other fields and no industrial engineering degree. Some have their entire education in a field other than engineering such as business administration or economics. Some have a 2-yr associate degree or in some cases, no degree at all. Thus, it appears that part of the problem lies in the background of some of the industrial engineers. They may not be in a position to utilize many available techniques. It should still be possible for the senior industrial engineers, many of whom hold a master's degree, to direct efforts to improve manual handling safety.

Actual Roles of Industrial Engineering

The actual roles performed by an industrial engineering staff with respect to manual material handling included the following functions:

1. Analysis of material flow and process coordination.

2. Economic feasibility studies of conveyors, stacking cranes, pallet designs, and alternative plans for shop and plant layout.

3. Basic work methods designs with most emphasis on what the operator does and how long it takes him and with limited attention to the effects of work methods and standards upon the operator.

4. Work measurement, standard data, and job description with limited understanding of the biomechanical or physiological aspects of work.

The major problems in achieving improved manual material handling safety seem to be:

1. The industrial engineer spends most of his time and effort on the direct economic aspects of work design.

2. There is little effort made to coordinate efforts among industrial engineering, safety, and medical departments to integrate job safety analysis into traditional work methods design. For example, tabulation of cycle elements in which frequent injuries occur could identify a work element needing to be eliminated or redesigned. This would be especially effective in a manufacturing system utilizing computerized manufacturing instructions or automated standard data.

3. Directives from top management related to manual handling safety rarely occurred. Middle management, industrial engineering, and first line management place emphasis on matters given priority by top management. A good example of influence by upper management occurs in decisions regarding product quality that originate as a management concept and are expressed at every management level and every phase of manufacturing from drawing board to loading dock with checks, controls, and corrective action predetermined. This type of organized effort is needed to eliminate manual handling hazards.

Potential Roles of Industrial Engineering

Potentially, industrial engineers can exert the greatest influence of any staff organization in a manufacturing facility toward the improvement of manual material handling safety.

This is true for a number of basic reasons. First, industrial engineers are in a position to justify improvements in safety on the basis of improved productivity and overall cost reduction. Second, industrial engineers constitute the only professional group with a formally assigned function of designing and improving work methods and standards and working conditions. Finally, industrial engineers have acquired a measure of expertise in dealing with management in their own organization since they are constantly receiving notices of problems and sending in recommendations and plans for changes.

Some specific ways in which industrial engineering can improve manual handling safety are:

1. Designing work methods to eliminate hazardous conditions and handling methods. Job safety analysis can be made an integral part of work methods design.

2. Working with the safety and medical departments to determine job elements that cause safety problems.

3. Ensuring reasonable work standards that do not encourage unsafe acts or a reckless work pace.

4. Auditing work methods to ensure that safe practices are being followed.

5. Developing, in cooperation with the safety department, job training aids that explain hazards and safe working methods.

6. Improving accident reporting methods to determine job elements that cause injuries.

7. Improving plant layout, eliminating congestion of in-process material, providing for safe handling of rejects, providing proper lifting height where conveyors are used, and assuring that lifting and moving aids are present where needed.

8. Performing economic analyses to justify in terms of productivity gains the use of powered and non-powered aids that reduce work stress and protect the human operator.

9. Using existing automated standard data and manufacturing instruction systems as a basis for developing hazard identification programs and for collecting data useful in epidemiological studies on a company- or industry-wide basis.

10. Using automatic work sampling to identify hazardous situations, events, methods, and postures.

11. Applying techniques of quality control and reliability engineering to the analysis of worker injuries as a "failure analysis" process currently applied to other aspects of manufacturing.

The overall purpose of industrial engineering must not be overlooked in considering improvements designed primarily to eliminate hazards and unsafe acts. Industrial engineering justifies its existence by lowering the cost of producing goods and of providing services. Often this is most effectively achieved through the elimination of activities that are found to be unnecessary or that add no value to the product or service. *In-plant material handling adds no value to a product. Therefore, any cost associated with it is a target for elimination.* To the extent that improvements in manual material handling safety also reduce direct operating expenses or factory overhead costs, they will be aggressively pursued as a part of total manufacturing system design. To the extent that they increase operating or management costs they will be resisted. It has been estimated that industry in the United States currently spends $20 billion annually in meeting a growing number of Federal standards and reporting requirements. This cost is real and must ultimately be borne by the consumer who in most cases receives no value added as a result of Federal programs. Safety and productivity will have to be considered on a common economic basis.

Material handling can be studied in terms of processes, operations, and work elements. In this respect, it is well suited for analysis by industrial engineers. Safety problems associated with material handling can often be identified or analyzed without significantly increasing the cost of studying operations. In the author's experience, most injuries occurred during an activity performed routinely or frequently. This suggests the use of existing methods and standards programs to identify and control hazards or to eliminate unsafe practices. The role of Federal manual material handling standards should be that of providing practical, cost-effective methods and guidelines for dealing with problems. It should not be one of forcing participation in an elaborate data collection program or one of imposing arbitrary or vague limitations.

RESULTS OF AN INDUSTRIAL SURVEY

During company interviews and plant tours, information was gathered by the author regarding:

1. Types of injuries and accidents frequently encountered.
2. Sources of injuries and accidents.
3. The use of job safety analysis.
4. Training programs.
5. The use of human factors and biomechanics.
6. Management attitudes and problems.
7. The roles of the safety, medical, industrial engineering, and other engineering departments.

With respect to the last five items, specific, positive programs were lacking in most cases. Also lacking was a coordination among the various departments mentioned.

Some general statistics for items 1 and 2 can be given for a few of the industries studied (Table 1).

Table 1. General material handling statistics by type of industry.

Type of industry	*Percentage of workers' compensation cost allocated to manual material handling injuries (A)*	*Percentage of (A) allocated to back injuries (B)*	*Other injuries as percentage of total workers' compensation cost (C)*
Sheet metal shops	20	75	Falling objects, 9; 22% of which involved foot and toe.
Forging works (drop or machine)	23*	60	Falling objects, 9; being struck by object, 8.
Tank trailer building	22	75	Falling objects, 7
Agricultural machinery manufacturing	18†	67	Falling objects, 7
Foundries (iron)	28	80	Falling objects, 11; contact with molten metal, hot objects, flame, 14, 50% of which involved burns to feet.
Automobile battery manufacturing	41	25	Sprains and strains, 50; contact with acid, hot lead, plastic, 11.
Electroplating	22	70	Falling objects, 19; contact with chemicals, 11.
Upholstering	36	75	Contact with material and nails, 14.

*Includes handling powered hand tools.
†Includes handling metal stock, parts, boxes, crates, and baskets.

The sample of data given in Table 1 indicates the magnitude of manual material handling considered as an overall company safety problem. The data given are typical of many industries. Strikingly evident is the high proportion of workmen's compensation cost provided for manual material handling injuries. The data agree generally with an overall estimate by the National Safety Council (1971) of 38.4%. The significance of back injuries as a percentage of this cost is also apparent. Column C indicates the significance of other injuries. Although some of these are not always associated with manual handling, all of them can be. Several facts are evident. First, there are many anatomical locations in which biomechanical overstress can occur. In some cases, injuries not associated with low back pain are the most common variety encountered. Second, many other injuries not involving overstress but resulting from hazards presented by the material or object handled or by the working environment (high shelves, crowded work area, sharp-edged material, etc.) account for a significant portion of material handling injury costs. Studies to eliminate or reduce these hazards are also warranted.

There are also many manual material handling hazards associated with mechanized handling. There is often a manual aspect in mechanized handling even though the work performed by the human operator cannot be classified as an unaided act of lifting, carrying, or releasing an object. Examples of such manual/mechanized activities include: guiding and positioning suspended loads and sorting or rearranging objects being deposited mechanically into a bin or being carried along a conveyor. Many pinching and crushing hazards exist in these situations. Injuries caused by falling material or containers are also very common. Being struck by empty slings, chains, and hooks is a problem in handling large objects.

Another currently obscure area involves "minor" unreported injuries that do not result in one or more lost work days. These may be minor in terms of severity, but their frequency is often very high. In one company surveyed by the author, the safety director kept a personal record of all such injuries and assigned a cost of downtime for the operator and his work station or machine. This cost ($9) accounted for 20 min of lost productive time per visit to the dispensary. The total monthly cost of these minor injuries was frequently over $10,000.

Relating industrial low back injuries or other types of biomechanical overstress to laboratory-derived biomechanical data can be difficult and even futile. Worker strength varies greatly among a given population (possibly as much as ten to one or more). Lifting methods also differ considerably. More research is needed to discover how people at work actually lift and handle material. The interrelationships among body size and strength and object size and weight need to be investigated so that criteria derived from modeling and simulation relate to actual lifting methods. Workers appear to choose through experience those methods and work paces that minimize their perceived stress and physical effort over time for a given level of accomplishment of assigned work. The biomechanical and physiological implications of these choices need to be discovered and applied in designing methods, setting standards, and selecting and training employees.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions to be drawn from this industrial survey can be divided into several categories. First, it was observed that in many types of industries, manual material handling accounts for the largest or one of the largest injury costs in terms of workmen's compensation. Back injuries comprised the largest portion of this cost in most cases. It was also observed that the industrial engineering function could play a most effective role in eliminating or reducing the hazards associated with manual material handling since it is heavily involved in work methods and standards and is also in the best position to coordinate an overall management effort to implement programs for improvement. A number of hazards and methods for eliminating or controlling them were outlined in previous sections.

Consideration of the overall magnitude of the problem leads to conclusions regarding the potential role of industrial engineering in total company, inter-company, and state or national level programs to control manual handling hazards. Few companies and none surveyed in this study are undertaking a general, company-wide effort to reduce manual handling hazards. The author has found it difficult to obtain detailed statistical information on a state-wide basis for this problem or for any other safety problem because of legal, proprietary, and administrative complications. The National Institute for Occupational Safety and Health, through a series of seminars, has constructed an extensive set of guidelines for developing criteria and standards for manual material handling safety. Many large companies, through their own industrial engineering departments, are in a position to explore the practical aspects and limitations of NIOSH recommendations through applied research and also as a part of their extensive methods and standards programs. When such developments take place in a coordinated manner (via university seminars, use of standard measures and definitions, sharing of data, etc.), the research efforts making this book possible will be brought to great fruition.

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THE ROLE OF SAFETY MANAGEMENT

D. F. Jones

When I talk on any aspect of safety, I have a tendency to antagonize some traditionalists so I might as well remain true to form. If you really want to know the best way to reduce total compensation cost associated with manual materials handling, I can give it to you in one sentence. *Fire any employee who complains about a sore back.* If an employee is fired before the back problem reaches one that warrants compensation, it now becomes the problem of his next employer. Even if the dismissed employee applies for workmen's compensation, you can still fight it, and you have achieved your intended result of making sure that no employee will complain about a sore back unless they want to be fired or are physically incapable of doing any work due to the magnitude of the pain. You may end up with employees who will drop arsenic in your coffee the first chance they get, but you will have achieved your intended result. This is the problem with many of our ill-conceived programs to reduce compensation costs—we look at a problem in isolation and ignore the total man and his interaction with other employees, the work environment, and such situations as he must face on the job.

If you think that the solution mentioned above is irrational, you are right. If, however, you believe that no one would do it, you are wrong. I have met such employers. In recognizing that such situations can exist and that they can throw our accident statistics for a loop, we must now determine the true nature of the problem and what safety management can do about it.

The question of the role of "safety management" is one that warrants a full seminar on its own. We will get back to it later, but let us first examine the type of problem requiring solution. There are two types of compensable back injuries. The first is the legitimate injury to any part of the anatomy that disrupts the stability and strength of the body when lifting, lowering, or otherwise handling a load. This load will vary from simple body weight to heavy awkward objects as would be encountered by a furniture mover. The second category is the minor ache we all have from time to time that, for psychological or other reasons, is magnified to the point that a compensation claim is filed.

The first category lends itself to physical measurement and diagnosis such that we can utilize some of the material presented by our past speakers to determine the cause and take corrective action. Unfortunately, the corrective action may lead to a worse type of problem if we are merely analyzing the physical components of the task without due concern for the lifestyle of the person suffering the injury. If the injury is associated with lifting heavy or bulky objects we can, of course, reduce the size or change the shape of the object or provide assistance in the lift or even mechanize the system. If we are dealing with reasonably* healthy, active people who get plenty of exercise off the job, this solution may be satisfactory, but if we are dealing with persons whose only physical activity is what they get on the job, we may be guaranteeing that their physical fitness will be reduced even further, thereby guaranteeing that a back injury will result the next time they bend over to pick up a pencil. The physical solution must therefore be accompanied by an analysis of the individual involved and action to remedy the underlying causes. Our second category involving minor aches blown out of proportion cannot be fully solved by physical changes in the environment but can only be minimized by creating a work environment in which the employees are adequately motivated to believe that they are part of a team that is doing worthwhile work and that their contribution is appreciated. You don't have to look very far to see the number of aches, pains, and diseases, which are supposedly not related to work, that show up when company morale is low.†

*"Reasonably," as used here, emphasizes two related hypotheses that warrant further study before defining objective criteria: (a) There is a relationship between failure under a given load or activity and the level of strength and coordination of the individual performing the task at that time. (b) Back injury is most prominent and severe in persons at both extremes of physical strength.

†The relationship between morale and health has received considerable attention in recent years, but the author is unaware of objective research to validate the relationship between occupational injury/disease and company morale. Personal observations including those of companies visited while compiling data for "Occupational Safety Programmes — Are They Worth It?" (Jones, 1973) consistently reinforce such an hypothesis. Further research on this topic appears warranted.

Back problems are not the only results of poor morale. In fact, morale problems masquerade under various names, and their solution may vary from a supervisor's word of encouragement to the provision of an executive sandbox. The same conditions that cause an hourly rated employee's back syndrome may result in an executive ulcer, and we cannot, therefore, discuss a physical disorder in isolation from the total environment of the individual.

This brings us back to our comment about "reasonably healthy, active people." I have been asked what I mean by "reasonable."Can I, for example, define a level of fitness which is "reasonable" to prevent back injuries? At this stage of our knowledge, I would be foolish to attempt such a definition since the level and type of fitness for a piano player must be different than that of a piano mover. Whereas the piano player requires rapid finger movement, while reaching from a sitting position, the piano mover requires prolonged muscular contraction of large muscles while standing. "Reasonable" in this context fits my definition of safety as "a poorly defined or nebulous area or condition lying somewhere between two unsafe extremes." This definition is modified in phraseology to suit the immediate needs, but the fact that both extremes are unsafe is always present. It might be said that our problems of occupational safety and health emanate from our failure to recognize this fundamental fact of life.

Although we may, as yet, be unable to clearly differentiate between "reasonable" and "unreasonable" or between "safe" and "unsafe," we must start somewhere, so let us take the extremes. Orthopedic surgeons have told me that back problems requiring their attention are found mainly in a person either badly out of condition or at the opposite extreme. This is consistent with a piano player being injured when trying to move the piano and the piano mover straining a muscle when attempting the rapid movements required to play it using different muscles in different positions from those that he is accustomed to using. Another way of saying this is that a jogger improves his fitness for jogging and a loafer improves his fitness for loafing. "Reasonable" fitness may therefore relate to a specific task or to a series of tasks. The loafer may therefore outlive the athlete—if he never exerts himself mentally, physically, psychologically, or metabolically. A prime purpose of a fitness program is to develop or maintain ability to cope with stress. To develop fitness to resist the wrong stress is therefore more dangerous than a lower level of all-round fitness since it may result in inappropriate and damaging muscular responses. In addition, the benefit of diagnostic mechanisms (which may include X-rays) as part of a thorough medical examination to discover potentially dangerous problems or disease previously unknown to the worker should not be discounted.

Recognizing these problems, I would not consider a person to have "a reasonable level of fitness" to perform manual material handling tasks unless that person is involved with tasks or exercise programs requiring bodily movement in all possible positions that may be encountered on the job. Such tasks or exercise programs must be performed frequently enough to maintain strength and flexibility but not so frequently as to develop postural or muscular fatigue.

Let us now go back to the role of safety management as it might relate to both types of compensation claims. If you think that safety management involves appointing an old and faithful employee who is no longer useful for anything else as your company "safety engineer," you are just about as brilliant as the person dying of malnutrition who finds a $100 bill outside of a restaurant and uses it to light a cigarette butt. The foregoing does not suggest that safety departments are not worthwhile; rather, if they are to be worthwhile, they must be staffed by people who are adequately trained to face the complex problems of technical safety and its interaction with people who come from varying backgrounds and with different attitudes to work and life (Jones, 1975). The incompetent "safety engineer" can do more harm than good not only through ridiculous, nonproductive and costly recommendations but through the creation of an antagonism towards anyone who has anything to say about occupational safety and health.

Perhaps the best way to recognize an incompetent safety engineer is that he generally thinks he knows all the answers to your problems. This does not mean that this rule is universally true or that the converse is also true, but it's a good start at avoiding incompetents and those who will create unecessary antagonism. Criteria for selection include both academic and practical experience, but these are useless without an inquiring open mind and ability to get along with personnel at all levels of the organization.

Academic qualifications should ideally include engineering and psychology (or human factors engineering), but the level of such exposure will depend on the complexity and technology of the industry. Some situations may require expertise in fire protection, whereas others will be in other technical areas. Nevertheless, all will be affected by interfaces between man, machine, and environment including other employees and the public. As such, an understanding of ergonomics becomes essential.

Since back injuries often account for more than 20% of compensation costs, and since safety programs still contain teachings incompatible with reality and unacceptable to most workers, and since recent research has proven that the employees are right, it is essential that we continue to conduct research into all aspects of manual materials handling.

In addition, we must publicize the physical, psychological, and other knowledge emanating from such research in a manner that is understandable to those who must use it in industry and in their personal activities. The payoff to industry (in reduction of industrial back injuries) that can emanate from such research and implementation of the results (particularly where an effective experience rating provision is contained in the Workmen's Compensation Law) could exceed $50 million annually in my home province of Ontario and likely more than $1 billion in the United States. It is unlikely that complete elimination of compensable back injuries resulting from manual materials handling can be achieved, but even a 10% reduction would (on a cost effective basis) justify an annual expenditure of $100 million in the United States if my figures on compensable costs are realistic. Since our statistics are less than perfect and since my interpretation of them is also open to debate, my estimate may be excessively high or low; but even if my figures are exaggerated, and ignoring the cost of off the job injuries from similar causes, the efforts currently expended on the problem are infinitesimal as compared with the potential benefits.

Let us assume that we have a reasonably competent safety department and know how to prevent back injuries. We are still going to strike out unless all levels of the organization are fully supportive of what is being done. If we now recognize that "safety management" does not relate solely to the safety engineer, the safety department, the foreman, or the company president but that it relates to the system of which they are all part, we have a chance of recognizing the role of safety management in minimizing injuries and compensation claims associated with manual materials handling and with any other downgrading incident in the operation.

Everyone should examine those things over which they have control—attempting to find ways to improve production of quality products, while reducing any employee's probability of injury (whether physical or psychological) to an absolute minimum. If you think you are going to prevent back injuries and compensation claims by merely introducing physical measures, I say *forget it* because it won't work unless it is accompanied by the kind of program that will make the employees want to participate and do their share. There are, of course, cases where the introduction of physical safeguards will make an employee embarrassed to complain about a back problem, but this doesn't mean that you are really solving it—so make sure that whatever you try is adequately evaluated.

Another controversial item is the question of preemployment X-rays. The way things are going lately I can see the cost of back injuries (as they existed before the preemployment X-ray program) being replaced by claims for cancer or other disease related to the X-ray exposure. No matter whether the preemployment X-ray did or did not cause the later cancer, you are likely to be in the same situation as you now are in—arguing whether the supposed back injury is related to a task that was performed at work. In addition, some studies have shown that a person with a supposedly normal back under preemployment X-ray is just as likely to have a back injury as the person with a diagnosed weakness (with some exceptions). The cost of X-rays would therefore be justified only if used for comparing the preemployment condition to a later spinal condition to help validate a claim rather than to prevent it. I suggest, therefore, that preemployment X-rays are most valuable to an employer who wants an employee to receive compensation when such compensation is justified but is faced with an insurer who is reluctant to pay such claims.

Let me reemphasize that the best way to minimize back problems associated with manual materials handling is to develop good employee-employer relations so that all employees are well motivated to perform their work efficiently and safely. If we start with this principle, we can examine each task to determine factors that will minimize individual injuries through such action as reduction of load, mechanization, planned exercise, and most importantly, the selection of employees physically and emotionally compatible with the task in the environment in which it is performed. The role of safety management is therefore more complex than reducing package size or weight, increasing mechanization, requiring preemployment X-rays, and ensuring that everyone lifts with their legs. Yes, it *is* more complex, but once we recognize that there is no one solution to fit all persons in all situations, we can select those components that are applicable to each employee in the situations under which that employee must work. A complex problem then becomes a series of simple ones. To achieve this, we must develop not one but a series of solutions from which each person can select and develop habits that will be personally suitable, productive, and protective. In addition, we must dispel the myths that have been foisted on North Americans in the name of safety for several decades.

One of the most common myths is that the back is a weak structure requiring constant protection and avoidance of stress. Since stress is necessary to survive and grow and since its absence results in deterioration, such teachings may increase back injuries and psychological back syndromes. But we can't even test the hypothesis until we have the courage to admit that such a relationship may exist. Perhaps, the greatest role of safety management today is to question existing teachings and encourage studies that will eventually define all elements of the problem and the most appropriate solutions.

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CHAPTER 5. SUMMARY

Davies has presented training programs that can be shown to be effective, and Adams has shown how industrial engineering can interface effectively with others concerned with this problem. Jones has rounded up some of the major controversial problems currently facing those directly responsible for industrial safety.

How can we infuse these workable strategies with the results of the latest research? How can researchers learn that the real problem is not merely bad backs due to lifting? How can we structure our intervention strategies to deal with all the problems and possible occurrences related to manual materials handling? These questions come into sharp focus when one tries to communicate thousands of pages of research papers to people whose day-to-day responsibility is to supervise production. Such people do not have the time to study manual materials handling safety (or any other aspect of safety) in any more depth than production scheduling, quality control, leadership dynamics, or any other of the thousand and one disciplines that make up the job of the skilled worker and supervisor.

After the Symposium was held, the editor received from John Lenhart a copy of the manual materials handling portion of the Bausch and Lomb safety manual with the question of how would he use the symposium data to change this presentation. This material is reproduced at the end of this chapter. It covers, as we suggest, job redesign, selection, and training; it shows the importance of the problem. Perhaps the things researchers should be adding to this are quantitative results—but should these be applied here or through staff functions of the company such as medical, safety, training, or industrial engineering departments? The challenge is not an easy one; the excerpt shown is one of the best of many such pieces the editor has seen. Yet if we cannot improve on this advice at the workplace, is all further research wasted? Consideration of other areas in which occupational safety has been improved over the last several years gives a possible answer. Supervisors and workers need to know about the hazards of such substances as asbestos, and management is ultimately responsible for control, but technical control of a hazard only comes with technical knowledge. General recommendations need not change with research findings but specific remedies to specific problems certainly will.

LIFTING

Twenty five percent of Bausch & Lomb's lost time work related injuries occur as a result of improper lifting. According to the National Safety Council, low back pain is second only to head colds as the leading cause of worker absenteeism. Right now throughout industry, seven million people are being treated for chronic backaches and new cases occur at the rate of two million a year.

It's generally assumed that people who do heavy work are the most likely victims of backaches. That's not necessarily true. Office people have nearly the same incidence of backache and lose nearly as much time as do production people.

Backaches are often attributed to physical characteristics — overweight people have more backaches than thin people, for instance, or tall or short people have more backaches than persons of average height. Actually, physique is only a minor factor in the cause of low back pain.

The most surprising information to come to light recently is that low back pain is usually caused by degeneration of the spinal discs. This is a condition which may start in the early twenties and is brought on by changes of the spine due to aging. An accident or strain from lifting is merely the climax of the basic cause.

In spite of this basic human handicap, the chances of back injuries and hernias can be greatly reduced by means of a three pronged attack on the problem: (1) eliminate manual lifting whenever possible, (2) select employees who are physically qualified for manual lifting, and (3) train employees in the right way to lift.

ELIMINATE MANUAL LIFTING WHEREVER POSSIBLE

As with all hazards, elimination will solve the problem forever. Modern mechanical lifting devices such as conveyors, power lift trucks, rope or chain hoists, drum pumps, hand trucks, jacks, and two wheel drum trucks can quickly repay their original cost by elimination of injuries. Usually production is increased as well.

SELECT EMPLOYEES WHO ARE PHYSICALLY QUALIFIED

How much weight can an employee lift safely? The answer is not easy because of many variables. These include bulk of object, shape of object, frequency of lift, weight, height of lift, possible necessity of twisting during lift, plus age, physical condition and physique of employee doing the lifting. Because of these and other variables, medical advice is essential to assist in determining how much an individual employee can lift safely. This advice should be sought prior to selection of employees who will do manual lifting as a part of their job.

TRAIN EMPLOYEES IN RIGHT WAY TO LIFT

Bausch & Lomb supervision is responsible to make sure that employees use the accepted modern method of lifting whenever they lift manually. This method is described verbally and pictorially as follows:

A summary of this correct lifting technique is contained on the card inserts in the following page. The importance of using these cards for on the job training of employees in sound lifting techniques cannot be overstressed. Additional cards may be ordered through Corporate Safety. Supervisors shall thoroughly instruct employees in the Right Way to Lift.

1. SIZE UP THE JOB. . . is it too heavy? Is it too bulky? Do you need help? Can mechanical means of lifting be used?

2. POSITION YOURSELF PROPERLY. . . feet spread about 20". . . one foot at side of object. . . other foot in back of object.

3. BEND BODY CORRECTLY. . . bend knees. . . keep back straight, but not necessarily vertical. . . incline back forward as necessary. . . tuck chin in.

4. TILT OBJECT. . . grasp freed bottom corner with one hand. . . grip firmly with palm of hands as well as with fingers.

5. LIFT WITH LEG MUSCLES. . . keep object close to body. . . arms in. . . chin in. . . make leg muscles do the work.

6. LOWER LOAD BY REPEATING STEPS 2, 3, 4, 5. . . avoid twisting throughout the lift, the carry, and the set down. . . remember, repetitive lifting and twisting, no matter how light the load, will sooner or later cause you trouble.

Don't Overlift - Get Help if Needed

Be Smart - Always Lift Properly.

A summary of this correct lifting technique is contained on the card inserts in the following page. The importance of using these cards for on the job training of employees in sound lifting techniques cannot be overstressed. Additional cards may be ordered through Corporate Safety. Supervisors shall thoroughly instruct employees in the Right Way to Lift.

New Way To Lift

2 3 of all male workers have a back problem sometime during their working years. A new way to lift has been developed to reduce these miseries. B&L Supervision should know and teach workers to lift using the following improved method:

Important Steps	Key Points
1. Position feet	- About 20" apart - One foot at side of object pointed in direction of travel - Other foot in back of object
2. Bend knees	- About 90
3. Tuck in chin	
4. Position back	- Straight but inclined forward as necessary
5. Grasp object firmly	- Use palms as well as finger tips
6. Tilt object (Except when object has convenient handles)	- Grasp freed bottom corner with one hand
7. Lift with leg muscles	- Keep object close to body - Avoid twisting body

DON'T OVERLIFT - GET HELP, ESPECIALLY IF YOU ARE "OUT OF SHAPE."

(over)

Other Ways To Prevent Back Miseries

1. When doing work that calls for bending, workers should squat - thus easing strain on back.
2. Standing for long periods with both feet apart but on floor can induce "sway back." The workers should be provided a way to keep one foot off the floor periodically.
3. If the work allows employee to sit, he (or she) should be able to raise one or both knees periodically. This will prevent back strain that could lead to serious (lost time) problems.

AVOID TWISTING, AND/OR OVERLIFTING -- THE TWO MAJOR CAUSES OF MOST B&L BACK INJURIES.

B&L Safety Department

CHAPTER 6

MANUAL MATERIALS HANDLING IN THE FUTURE

INTRODUCTION

It has been traditional to bemoan the existence of widely divergent recommendations for maximum weight lifted that are found in the literature. These divergent recommendations have actually been due to the differences in what is accepted as a reasonable criterion by different authors and even due to lack of precise definition of the tasks within the broad field of manual materials handling.

The four most obvious limitations to manual materials handling performance can be seen, from the diagram at the end of Chapter 4, to be:

1. The worker's skeletal, ligamental, etc., strength or resistance to damage with respect to stresses imposed by task demands.
2. The worker's torque production capabilities, both short-term explosive strength and long-term endurance, with respect to task demands.
3. The worker's energy production capabilities with respect to task demands for energy production.
4. The worker's cardiovascular capabilities with respect to task demands for energy production and thermal load.

It is generally agreed that the first two of these account for the great proportion of medical complaints in manual materials handling, with particular emphasis on traumatic injury to the spine—the low back problem. As Troup pointed out, there are obvious difficulties in diagnosis and classification, but reliable epidemiological evidence of the relationship between load-handling and medical complaints has now been demonstrated in the Herrin and the Davis and Stubbs papers.

The three measures that should be related to low back stress are the stress itself, usually on the L5/S1 disc, estimated largely with the aid of biomechanical models; the intra-abdominal pressure that has been demonstrated to correlate with disc stress; and the subjective willingness to tolerate a task that produces low back stress, measured psychophysically. It is interesting that papers at the Symposium present all three methods and show substantial agreement. They are in agreement on both the factors that have effects on disc stress too large to ignore and, to a reasonable degree, on the range of loads or weights that would be likely to cause problems.

For the act of lifting, the major factors would appear to be:

- the weight of object lifted,
- the position of the hands in relation to the spine,
- the individual's muscular strength, and
- the frequency of lifting.

This convergence between research technologies, even to the point where similar absolute magnitudes of weights are being suggested as limits by various techniques, suggests that some sensible recommendation for government action may become a possibility in the near future. With this general background in mind, the three workshop sessions organized at the Symposium were charged with making recommendations for research priorities.

One group, composed mainly of medical personnel, addressed itself to research priorities in the medical aspects of the problem. The second was asked specifically which factors would have to be included in any standards or limits. The third group looked at the role of personal prevention programs. All participants were deeply immersed in the problem, and the chairpersons chosen had international input at the highest level. Strict time limits were set to allow the chairpersons to keep the discussions on the most relevant topics. Each participant chose which workshop to attend on a voluntary basis.

The reports emerging from these workshops were discussed, even argued over, in a final plenary session. The reports of the three workshops follow.

WORKSHOP A. MEDICAL ASPECTS OF MANUAL MATERIALS HANDLING

A. Nachemson and J. D. G. Troup, co-chairpersons

The overall medical and economic problems of manual materials handling are great as has been exemplified and partly substantiated during this conference.

The difficulties from a medical point of view lie in recognizing the existence of a proper trauma and injury. Only approximately 20% of the workers with a back problem have a definitely recognizable trauma or injury leading to back pain. Unfortunately, the existing recognizable signs, clinically and/or radiographically, are not conclusive.

Although we recognize that other medical problems in conjunction with manual materials handling are in no way negligible, amounting to 20% to 40% of the reported injuries, their cause, prevention, and treatment are more obvious and their reporting is more accurate. These other injuries, like sprains, strains, bruises, cuts, etc., can, therefore, be handled separately; and since they account for a minor percentage of the total costs of injury arising from manual materials handling, they will not be dealt with in this discussion.

With regard to the back problem in relation to manual materials handling, we are not able, at the present time, to define the overall medical problem because of discrepancies in reporting.

This calls for uniform manner of reporting injuries both in various countries and internationally. A clear definition is necessary. The episodes leading to back pain must be subjected to more thorough investigation.

Despite the lack of knowledge of the etiology of back pain—which must be subjected to research sponsored by agencies other than NIOSH, for example NIH—present knowledge of the mechanical and other factors involved calls for certain recommendations now.

We are in urgent need of *methods of job description*, for example, peak trunkal stress; total trunkal stress per unit shift; posture description; peak energy expenditure; environmental stress such as heat, cold, vibration; characteristics of loads to handled. It is necessary that these descriptions should be made as simple as possible for use in the preplacement evaluation procedure.

Dependent upon the job severity or situation, the *preemployment examination* or any examination performed in the factory to change the employees' job situation should be differentiated on a scale of increasing job severity.

The examination, which can be subjected to further inclusions or reductions after investigations, should include:

- test of muscular strength,
- capacity for energy expenditure,
- endurance,
- pulmonary function,
- anthropometric characteristics such as height and weight,
- previous medical history,
- complete physical examination including joint mobility.

Under special circumstances, if recommended by the examining physician, tests like ECG, psychological tests, and spinal X-rays should be included.

A prospective multificatorial study of all these variables in relation to job severity will tell which factors are the most important to prevent back injuries.

It is important to identify different individual factors and job factors in relation to injury rates in manual materials handling.

Already, at our present level of knowledge, certain recommendations can, however, be made in relation to preemployment examination, and such recommendations should be worked out under an expert panel sponsored by NIOSH. To a certain extent, some of the knowledge necessary for such recommendations can be found in the various reports given by Troup, Snook, and others of the symposium. Recommendations should be worked out by an expert panel including specialists with relevant backgrounds, such as orthopedic surgery; internal, physical and industrial medicine; work physiology, etc.

Although both training and removal of environmental stressors have been shown in this symposium to be useful in reducing physical and mental strain in manual materials handling tasks, further research is needed to evaluate qualitatively the effectiveness of such programs.

The relationship between time of exposure to risk and illness can be determined after the already-mentioned job and individual factors are evaluated over long time periods.

WORKSHOP B. FACTORS NEEDED TO DEFINE STANDARDS

P. R. Davis and S. H. Snook, co-chairpersons

When considering the factors necessary to define standards or limits for safe manual materials handling, we first recognized that many types of injury arise from manual materials handling; however, we focused attention on lower back pain and its prevention.

Throughout, we were conscious of the presence of the many factors that have importance in different specific tasks and situations. Those given below were believed to be the most important for people who have to achieve the simplicity of general standards.

Three groups of factors were considered, and we selected from each those few that appeared to us to be important in creating a simple answer to this complex question.

1. Different types of handling tasks, ranked in apparent order of importance:

- lifting (where most injuries occur),
- repositioning the load without steps (inducing body twisting),
- repositioning with steps (i.e., carrying), and
- releasing (lowering, dropping, throwing).

2. Different characteristics of handling tasks (recognizing that many other characteristics have importance, such as space limitations and environmental considerations, but that, for this purpose, these three are the most that could be used at the present time):

- magnitude of the load,
- frequency of task repetition, and
- dimensions of the object—size of the load and its position in relation to the body.

3. Difference between individuals (believing these may be best accommodated by creating one three-zone standard; a two-zone standard would exclude the second zone (below) and would need many standards and be difficult to apply):

- no restrictions,
- screening for individual capacities (sex, age, strength, handicaps), and
- prohibited.

Although, at present, the most comprehensive zone boundaries are provided by psychophysical approaches and individual screening is best supported by biomechanical and physiological tests, further analysis of existing illness, injury, and other data could provide more stringent criteria for those boundaries. We recommend that this composite approach be adopted in establishing these limits.

WORKSHOP C. NIOSH NEEDS IN PERSONAL PREVENTION PROGRAM DEVELOPMENT

D. B. Chaffin and R. H. Jones, co-chairpersons

It is the consensus of this Workshop Group that an eventual occupational health and safety standard pertaining to manual materials handling shall need to include a well-defined administrative program of preventive practices for individual workers. This is substantiated by the fact that human attributes related to personal susceptibility to injury and illness due to the excessive stresses of manual materials handling vary so greatly in the working population (e.g., the strength of healthy workers varies by over a 10:1 ratio). Because of this, the eventual standard must not only specify where engineering controls are needed to eliminate the hazardous stresses on all workers, but must concentrate on how workers who have diverse attributes are selected, placed, trained, and evaluated.

In this regard, the following recommendations are made to NIOSH with the hope that they will stimulate the much-needed development work towards the control of the enormous costs and human suffering related to the hazards of manual materials handling.

1. Functional Task Descriptions

Currently, job descriptions are poor to valueless indicators of the potential stresses and strains of the job, either physiologically or psychologically. Therefore, systematic efforts to identify and screen for health hazards gain little help from their use. Furthermore, the ability to match individual assets and deficits with the functional demands of the job is impaired, with the result that the potential for mismatch is high. Finally, a job description bereft of the functional demands of the task does not help the trainer in his/her effort to develop appropriate knowledge and skills in the trainee.

Proposal: NIOSH needs to develop methods by which the functional requirements of the manual materials handling tasks will be identified. These may include such task characteristics as: load handled, frequency of handling loads, postures, pace, and enviromental conditions.

2. Data Retrieval and Reporting Techniques

Because it is necessary to identify the diverse characteristics of jobs and workers that create injuries and illnesses before they become serious, better medical data reporting techniques should be developed.

Proposal: NIOSH should undertake to investigate and promulgate better medical reporting and evaluation systems for use by industry in regard to manual materials handling.

3. Selection Criteria

At present, it appears that selection criteria for employees being placed in manual materials handling jobs are not universally applied or validated.

Proposal: NIOSH should further develop and evaluate personnel selection and placement criteria that relate to the stresses of specific manual materials handling jobs. For instance, the use of tests of worker strength and endurance and various anthropometric measures appear to have promise and should be further evaluated.

4. Training

There are many methods proposed for safe handling of loads advocated by various groups. Unfortunately, there is no convincing evidence that any one method provides better protection than others. Thus, it is premature to support one specific concept at this time.

Proposal: NIOSH should undertake a controlled longitudinal study of the protective value of various methods.

5. Training in Manual Materials Handling Jobs

Training would appear to hold great promise as a preventive medical practice. It is not clear, however, what the nature of these training programs should be. The only general criteria would appear to be that they should involve the worker actively in the learning process and identify specific techniques and hazards of the manual materials handling jobs.

Proposal: NIOSH should undertake to develop and evaluate both the short- and long-term consequences of training programs for workers assigned to manual materials handling jobs.

6. Container and Workplace Design

It is recognized that many MH containers and associated workplaces do not recognize the large variations that exist in the working population today. A need exists to ensure that good ergonomic principles are used in the design of MH containers and workplaces.

Proposal: NIOSH should undertake to develop ergonomic guidelines for the design of commonly used MH containers and workplaces to ensure that the large variations in worker population attributes are accounted for.

RECOMMENDATIONS

The proposals that emerged from all three groups concern both the probable content of standards and the research deemed necessary to develop the standard. It was particularly evident that no group was at all satisfied with the *status quo* with respect to manual materials handling jobs in industry. Also evident was the need for epidemiological measures against which to measure the benefits of change. There are three types of measures of system performance.

- **Outcome measures** of system effectiveness, such as injury rates, death rates, lost time through injuries, etc. These measures represent the ultimate criterion of how well a system is working but obviously demand costly, well-controlled studies in a real-world setting for their use.
- **Process measures** such as intra-abdominal pressure, heart rate, etc. These are measures that show the internal workings of part of the system, in this case the human operator. They are measures that, it is generally agreed, should be maintained within strict limits for good system performance; however, the relationship of process measures to outcome measures has not always been measured and has generally not been found impressive when measured.
- **Input measures** such as compliance with regulations, size and cost of safety department, number of medical preplacement examinations, etc. These measures show the deployment of resources made by the system without reference to the effectiveness of these resources. Despite the fact that they only measure potential performance, they are easy to obtain and, therefore, frequently form the basis of many industrial and government reporting systems.

For example, in the manual materials handling field if or when a set of numerical standards are issued, compliance would usually be measured as an input measure, but performance would be monitored as an outcome measure.

The clear need expressed in the workshops is for some validation of input and process-derived results against outcome measures. Models and process measures are still needed to provide meaningful scales against which to correlate outcome measures. For example, discal stress at L5/S1 could well be the common denominator with which injury rates on a number of jobs are compared; this would usually be obtained from biomechanical models.

Herrin's study, and its antecedents, provide a prototype for such investigations. Here, correlations are sought between outcome measures, such as injury rates and lost time, and personal and job factors. These factors are carefully selected on the basis of models or other compilations of the literature so as to have the maximum *a priori* chance of "explaining" the outcome measures. Such studies do not represent all that is now required by any means; rather, they appear to fulfill the unmet needs most rapidly.

With this preamble, it is possible to recast the workshop's recommendations to bring them together. Workshop B proposed a form of a standard rather than a research policy. The elements from this workshop have been incorporated into the following summary recommendations.

RECOMMENDATIONS

A safety standard in manual materials handling is not possible without some additional research. However, it is possible to specify the form *of such a standard aimed specifically at reducing the low back injury associated with manual materials handling activities. A single "maximum object weight" would be grossly misleading; any definition of the job must include these factors:*

- *type of handling operation, e.g., lifting, pushing, carrying, etc.;*
- *weight of the load to be moved or held;*
- *size of the load and its position relative to the worker's body; and*
- *frequency with which the task is repeated.*

Individual differences in strength are so large that they must be explicitly incorporated into the standard. This is best done using a three-zone standard, with the first zone representing no restrictions on handling, the second representing a requirement for preplacement testing of workers to ensure that they are capable of working without damage, and the third zone representing complete restriction on manual handling.

To achieve this standard, these research areas are defined as having the highest priority:

1. Improvement of outcome measures studies

Improvement is needed in the area of clarifying diagnosis of low back injury, improving reporting systems for medical outcomes, improving descriptions of manual materials handling tasks, and improving preplacement examination procedures for workers. Such improvements would be beneficial by themselves, but, taken together, they also provide a data base necessary for the epidemiological studies listed below.

2. Outcomes as related to job/worker matching

Because the job and the worker cannot be considered separately, well-controlled epidemiological studies are needed to determine the effects of the following factors on safety outcome measures:

- *times of exposure to known jobs,*
- *batteries of preplacement tests or examinations for known jobs,*
- *types of handling technique trained for in known jobs,*
- *methods of construction of training schemes for known jobs,*
- *ergonomic "good practices" in workplace and container design for known workers, and*
- *environmental factors affecting known workers.*

3. Effectiveness of a standard

From the above studies will come a wealth of valid data on injury rates in many industries related to aspects of job design and personnel selection and training. From this data base, it should be possible to estimate the effectiveness of any proposed standard by measuring the number of unfavorable outcomes that full compliance with the standard would have eliminated. In addition, the difficulty of implementing such a standard in terms of the percentage of manual materials handling jobs requiring redesign could be estimated. These two factors of effectiveness and the factor of cost as a function of the numerical values contained in the proposed standard should provide a rational basis for future decision making regarding standards for manual materials handling safety.

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