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Development of methodology in biomechanical simulation of manual lifting *

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Abstract

The purpose of this paper is to introduce some techniques of biomechanical simulation through an example – simulation of manual lifting. The motivation for developing biomechanical simulation is discussed. Biomechanical simulation is defined and compared with the traditional biomechanical modeling. The formulation of biomechanical simulation of manual lifting is presented, and some practical techniques used to conduct a simulation of manual lifting are provided.

Relevance to industry

Back injuries are a serious problem in terms of human suffering and cost for workers and their employers. An ergonomic approach to solve the problem is to redesign the manual materials handling tasks to fit human characteristics. For such an approach, human motion patterns under different lifting tasks should be understood and predicted.

Key words: Biomechanical simulation; Optimization; Kinematics; Kinetics; Motion patterns; Angular displacement; Polynomials

1. Introduction

Occupational biomechanics is concerned with the application of mechanics to the man–task-environment system to reduce mechanical stresses on the worker's musculoskeletal system while maintaining high performance levels. Occupational biomechanics is quite useful in:

(1) understanding motion patterns (displacement-time information) required by jobs;
(2) estimating the kinematics and kinetics of these movements;
(3) calculating the stresses imposed on various body parts as a result of a specified job execution.

In investigating the industrial job-related safety problem, it is helpful to evaluate distribution of forces and torques to various segments, joints, and soft tissues. For example, through such evaluations of the job-related physical stresses imposed on a worker, a potential means of reducing

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the high incidence rates of manual lifting injuries could be realized. However, there is no device that can be applied to directly measure forces on each joint of the human body during lifting without any interference with the motion or potential damage to the subject's body. Consequently, biomechanical modeling, especially when based on cinematographic data, serves as one of the least invasive methods in investigation of body movements and the kinematics and kinetics of these movements. These models are a representation of the system in order to understand its behavior. Often simplification and assumptions must be made (Chaffin and Andersson, 1991).

By using a biomechanical model and comparing the model's behavior with the behavior of the system, such as in the case of manual lifting, an insight about how the system functions and the interactions between its components may be gained. Nevertheless, to conduct a dynamic biomechanical analysis, displacement-time information for the various joints of interest must be known in order to estimate the kinematics and kinetics of the movement. The collection of such displacement-time information is a tedious countenance of dynamic biomechanics. Such data collection must be made for all task combinations to be studied prior to the analysis and requires specialized equipment and trained personnel. With the development of simulation models, it is possible to provide an indirect means of performing the kinematic and kinetic analysis without collecting the displacement-time information. Thus, the first incentive for the development of biomechanical simulation is to facilitate more timely and convenient analysis.

Another incentive for biomechanical simulation development is to conduct a "reality check" of biomechanical modeling. "Biomechanics uses laws of physics and engineering concepts to describe motion undergone by the various body segments and the forces acting on these body parts during normal daily activities (Nordin and Frankel, 1989)". However, biomechanics cannot be used to exhaust and explain every characteristic of motion patterns; some of the characteristics may be psychological; some may be physiological; and some are simply unknown. The embedded interest is to appraise "how much of (or how real) the motion patterns can be synthesized" based on the laws of physics, engineering concepts, and the contemporary understanding of biomechanics derived. Such interest has been developed over the years (Saunders et al., 1953; Penrod et al., 1974; Chao and An, 1978a, b; Schultz et al., 1982, 1983; Hemami et al., 1982a, b; An et al., 1984; Pandy and Berme, 1988; Amirouche et al., 1990; Han et al., 1991; Karlsson and Peterson, 1992). It is clear that most of the researchers were interested in the optimization of the distribution of muscle forces about certain joints, and seldom focused on the prediction of the motion patterns required for job analysis. Furthermore, a very large body of literature harangued the synthesis of human gait, some address simulation of upper extremities, and few focus on the simulation of manual lifting. Thus, biomechanical simulation, especially of manual lifting, can be considered as the intrinsic evolvement of biomechanical modeling. As a general categorization, the major differences between the two are described in the following paragraph.

Biomechanical models usually apply the inverse dynamics, and biomechanical simulation apply the forward dynamics. Biomechanical modeling is a deductive method to describe the actual body motion, and biomechanical simulation is an inductive method to generate body motion patterns for an either existing or developing man–task-environment system. Biomechanical modeling employs kinematic and kinetic analyses to recapitulate "how fast or how slow" certain motion is and "what force, from what position", can initiate the motion. Biomechanical simulation employs kinematic and kinetic analyses and optimization techniques to filter the number of potential motion patterns from an infinite number to a feasible number of patterns to perform a task.

2. Foundation of biomechanical simulation

The foundation of this paper is based on the premises that (1) human motion can be simulated, (2) a decision rule is required to select a

motion pattern from various possible motion patterns, and (3) that decision rule, if there is one, for the most suitable motion pattern can be approximated by optimizing certain objective function(s). The first premise starts from the argument that human motion has certain repeatability. The human body performs particular physical activities using similar motion patterns. Fig. 1 demonstrates an overlap of four actual displacement-time plots for a lifting task (the same task performed by the same subject) which demonstrates a dependable envelope due to the similarity and variation of the motion (Lee, 1988). It should be noticed that both the portion of similarity and the portion of variation of the envelope are the fundamental constituents of biomechanical simulation. The portion of similarity reverberates the consistency of motion patterns, and the portion of variation reverberates the feasibility of several motion patterns.

The idea of optimization of human body movement has been recognized very early. Nubar and Contini (1961) postulated that "in all likelihood the individual will, consciously or otherwise, determine his motion in such a manner as to reduce his total muscular effort to a minimum consistent with imposed conditions". Basmajian (1962) identified the principle of minimal muscle effort as

Sherrington's reciprocal inhibition principle. MacConnaill (1967) stated that no more total muscular force is used than is necessary and sufficient for the task to be performed. Arvikar and Seireg (1978), Seireg and Arvikar (1973, 1975a, b), concluded that it would be desirable for the Central Nervous System (CNS) to coordinate the task by seeing that the muscle not exert too laboriously while the equilibrium of the joint was maintained, and that the forces transmitted by the joints not be too costly. Their objective function can be expressed by the following:

$$w_1 \sum R_i + w_2 \sum Mj + W_3 \sum F_k$$

where w_1, w_2, w_3 are the arbitrary weights, $\sum R_i$ is the sum of all muscle forces, $\sum M_j$ is the sum of reaction moments at the joints, and $\sum F_k$ is the sum of all reaction forces on the joints. In general, the objective functions of biomechanical simulation can be any formulation of conceivable kinematic or kinetic measures from the investigation of biomechanical modeling, such as, minimal joint force, minimal joint torques, or minimal work done, etc.

However, there are some disputes concerning the optimization approach. Berbenel (1972) used EMG to validate his optimization model and concluded that optimality does not apply to the
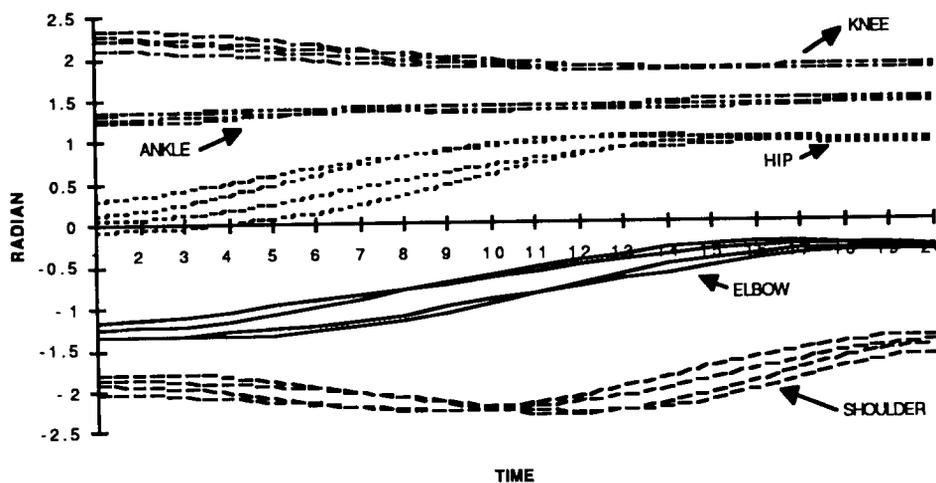

Fig. 1. The overlap of four displacement-time information from the same subject performing the same sagittal lifting task demonstrates both characteristics of motion pattern: similarity and variation.

biomechanics of the temporomandibular joint. Yeo (1976) studied the elbow joint and concluded that the principle of minimal total muscular force is unlikely to be true based on physiological and physical considerations. Genaidy and Houshyar (1989) took an even more stringent position. They summarized that despite the prevalence of the optimization approach in biomechanical research, the question as to whether optimization is applicable has not been resolved. They remarked that it has not been demonstrated conclusively that muscles behave in an optimal manner. Intuitively, the most direct objection to the optimization approach is that many movements, particularly those in everyday life, may be "satisfying" as opposed to "optimal". Most human behavior is performed with some sense of purpose in mind, such as decrease fatigue, decrease stress, decrease strain, or increase performance output. For many tasks for the industrial population, a conservative movement strategy that simply satisfies some basic, perhaps "fuzzy" objective (criterion) may be adequate to fulfill "the sense of purpose" (Hogan and Winters, 1990). Another aspect of the "satisfying" argument is the concept of desiring a certain margin of safety or stability. More specifically, there is no reason and no necessity for an ordinary person to live on the edge. Furthermore, certain tasks may be hard to specify by a performance criterion. Consider an optimization model for picking up an object on the floor and putting it down on the desk without undue effort. It includes:

(1) computation of all the kinematic and kinetic information;
(2) simultaneous control of many body parts;
(3) inherent redundancy, that is, the possibility of performing the same task by different combinations pattern of motion made of kinematics and kinetics of different body parts.

Therefore, for industrial or daily activities, the ideal objective function selected should reflect the conservative and complex consideration of human motion. Such an objective function might exist, but is difficult to define. An alternative is to generate a family of feasible motion patterns and randomly embrace one. The random selection, without any decision-making process, may still serve the need for biomechanical simulation mentioned in the previous section. The counterclaim is that optimization may provide more information than random selection. Given a musculoskeletal system, the optimization approach restates the problem from choosing among an infinite number of possible joint movement patterns into an equivalent problem of choosing among an infinite number of possible objective function values (of performance criteria). Because the objective functions can be chosen to delineate any biomechanically meaningful criteria, the primary strength of the optimization approach lies in observing how predicted motion patterns change with changes in the relatively different objective functions.

Thus, each motion pattern is really an outcome of a control mechanism indexed by a calculated value, and the same motion pattern can be indexed with different values when the control mechanism changes. Chow and Jacobson (1971) proposed a hierarchical structure for the locomotion control system. Researchers, especially in the field of experimental psychology, are inclined to use the system approach to explain motor control (Schmidt, 1982). They use the concepts of open-loop, closed-loop, feed-back, and feed-forward to explain how human bodies control and learn to control the movements. Essentially, they are also interested in answering the following questions:

(1) Does the human body have a mechanism to coordinate or distribute the work load to different body parts?
(2) Suppose a coordination (maybe optimization) mechanism is embedded in the human body, how does it work?
(3) Is the mechanism like a blueprint in the human body prescribing the motion pattern before the motion starts?
(4) Does the mechanism function like a feed-back or feed-forward loop determining how to move based on the current position and the related kinematics and kinetics?

It is beyond the scope of this paper to elucidate the above questions; however, the optimization approach can provide a testing ground to systematically examine them. In addition, the optimization approach has the nature of continuous

constraint verification, error evaluation, and iterative adjustment. This nature, in essence, imitates the composition of the system approach and provides another reason to choose optimization rather than random selection in biomechanical simulation. The primary goal of this paper is to demonstrate some methods for developing a biomechanical simulation.

3. Research procedures

In order to demonstrate some of these ideas in this paper, a project of simulation of a 5-joint (elbow, shoulder, hip, knee, and ankle) sagittal plane lifting is used as an example to discuss the various aspects of biomechanical simulation. Generally, in this study of the development of biomechanical simulation, the research was divided into three phases. The three phases, with separated activities, were closely related. In Phase I, observations of different lifting tasks were made and estimated kinematics were documented. In Phase II, the observations from Phase I were used to make assumptions, and to build required components of a biomechanical simulation model. In Phase III, observations were made again and compared with predictions made by the model developed in Phase II. Therefore, review and re-evaluation were planned activities in the three-phase research procedures. That is, the theoretical soundness of the model in Phase II was verified and validated in Phase III, and the precision of experimentation in Phase I really determined the quality of the model in Phase II. The following were the major activities conducted in each phase of this study:

Phase I – Pre-model development analysis:
An experiment was designed and the following variables were decided:

Independent variables:
(1) Subjects – Four male subjects;
(2) Lifting Ranges – 2 ranges
   Floor-to-knuckle height (FK);
   Floor-to-shoulder height (FS);

(3) Container sizes – 2 sizes, size A and size B;
   Size A (length: 24 in, width: 12 in, height: 12 in);
   Size B (length: 24 in, width: 18 in, height: 12 in);
(4) Number of repetitions of each task: 4 repetitions;

Dependent variables:
(1) Load – one-time maximal acceptable weight of lift, determined by the psychophysical approach;
(2) Displacement-time information for all 5 joints and the load;

The Data collection for this part of the research was accomplished through the use of cinematography. "Expert Vision" a UNIX-based motion analysis system was used to describe the motion in numerical values. The laboratory experimental efforts were employed for the purposes of (1) generating a lifting displacement time relationship and (2) comparing joint-torques with predicted joint strength values. Specifically, extensive lifting performance data were collected to generate angular displacement time relationships at the five major joints. These relationships were used to estimate the ranges of joint motion (ROM), the ranges of joint angular velocities, angular accelerations, and rates of change of angular acceleration for lifting activities to be used in the formulation of the mathematical model. The data were also used to determine the time variant torques produced during the lifting movement at each joint.

Phase II – Model development:
There were three decisions to be made in this phase: (1) decision on the components and structure of simulation, (2) decision on the function of every component, and (3) decision on the optimization algorithm. The details of this phase will be discussed in the next section.

Phase III – Model validation:
Since there were variations of the human body (e.g., different heights, different weights), variations of the tasks (e.g., different sizes of contain-

ers, different loads), and variations of the work-stations (e.g., different initial and final lifting level), it seemed very unrealistic to simulate and validate every possible combination of variations. If the actual data of every combination of lifting by different subjects were available, there would be no direct need to use the simulation approach. In fact, since there were limitation of manpower, equipment, and time, the only way to validate the model was through new samples. During this phase, a new lab experiment was conducted, and lifting tasks were simulated using the developed model. This new experiment with four additional subjects in Phase III followed exactly the same experimental design as Phase I. A verification procedure was conducted to justify the homo-geneity (similarity) between the experimental (measured) trajectory of the joint and the corre-sponding trajectory generated by the model. This procedure was done in terms of both trend and closeness of two behaviors while subjected to different task variables. The results will be dis-cussed in the final section.

4. Problem formulation

Simulation of human body motion was consid-ered as a multi-disciplinary in this study. It re-quired combining information from the biome-chanical and psychophysical approaches of er-gonomics with knowledge of behavioral sciences.
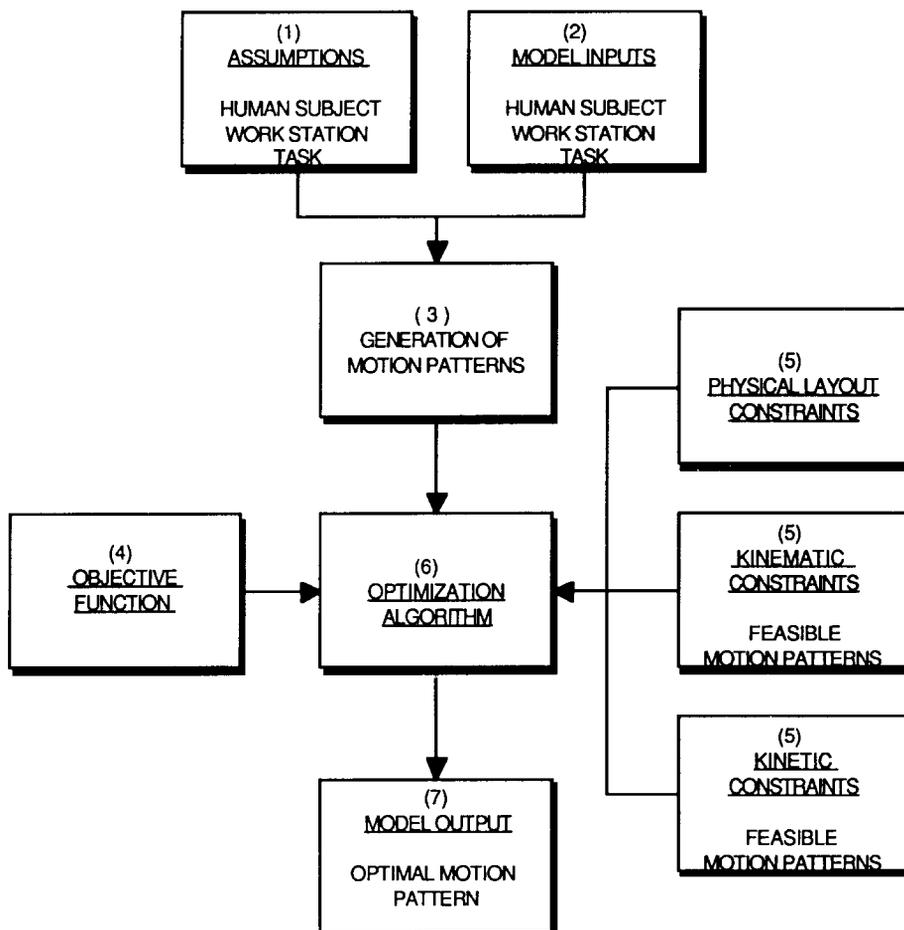

Fig. 2. The major components of a biomechanical simulation model.

Currently, two different methods to formulate the human body motion are available. The first method is to use Lagrange's equations of motion (Winter, 1990; Onyshko and Winter, 1980), where the Lagrangian function is defined as the difference between the total kinetic energy and the total potential energy in the system. Lagrange's equations of motion are convenient because the unknown can be chosen to be the body position and orientation, and the energy equations can be chosen to be in any convenient set of coordinates. The second method is to apply Newton-Euler equations for each link to solve this system of equations using the constraints that the links were connected. This paper discusses the second method for the problem formulation because some previous studies of biomechanical modeling (Chaffin, 1969; Ayoub and El-Bassoussi, 1976, 1978; Freivalds et al., 1984) were applied and compared with the results of simulation. Patriarco et al. (1981) concluded that improvements on existing optimization models were more highly dependent on the accurate determination of joint angles and the calculation of joint torques than on the particular optimization criteria employed. Therefore, it was determined in this paper that the major variables of simulation of manual lifting were the joint angles and the joint torques at the skeletal level of the whole body motion, and the interest to extend the optimization to the muscular efforts of every single joint was not considered at this time.

In this paper, biomechanical simulation dealt with only one set of performance limitations – those produced by the comprehension of human physical capacities and task requirements. In general, Fig. 2 shows that a biomechanical simulation (model) is formulated by the following parts: (1) model assumptions, (2) model inputs, (3) motion patterns generator, (4) objective function, (5) constraints set, (6) the optimization algorithm, and (7) model outputs. In studying the joints behavior during manual lifting activities, the primary assumptions were as follows:

(1) The human body, when viewed from the sagittal plane, was presented as a five rigid links model.

(2) The links were pin-centered at the joints.

(3) The density and the contour of each segment remained the same.

(4) The subject did not walk with the load.

(5) Every lifting task was independent from the others, and started from a stationary posture. As such, no voluntary movement was allowed before the beginning of the lift. For each joint j at time $t = 0$, the angular velocity was set $\dot{\theta}_j(t = 0)$ to zero.

(6) Tossing the container was not allowed at the termination of the lift. Especially at the end of the movement, the container must be lowered to the surface of the workstation. The total time to perform the lift is set at $t = T$. All joint movement was considered stopped at the end ($t = T$); thus, the angular velocity $\dot{\theta}_j(t = T)$ and the angular acceleration $\ddot{\theta}_j(t = T)$ were considered very small values and approach zero.

(7) All movement during the lift was symmetrical; that is, each arm moved in unison with the other arm as did the legs.

(8) Restorative passive moment provided by the ligamentous tissues (Gracovetsky el al., 1981; 1985; Anderson et al.. 1985; Schultz et al., 1987) were not considered.

(9) No abduction or adduction of the arms were considered.

Clearly, some of the assumptions were made to simplify model complexity, and some were based on true observations. The inputs required by the simulation were

(1) information about the subject's anthropometric characteristics, including body weight, stature, and the selected segment lengths;

(2) information about the workstation's dimensions, including its relative position to the human segments;

(3) information about the task, including container size (length * width * height), container weight, and time to accomplish the task.

(4) the initial static body postures, including all the joint angles required to depict the starting position of the task.

(5) the final static body postures, including all the joint angles required to depict the ending position of the task.

On the basis of the model's assumptions and input information, a motion patterns generator continuously produced a large number of motion patterns. The generation of motion patterns, as a key mission in this paper, is discussed in the next section. The feasibility of each motion pattern was evaluated after being generated. Hemami (1980) classified constraints into four categories: connection, locking, reaction, and collision. With considerations similar to those of Hemami (1980) the constraints set of this model were the following:

(1) To determine the range of motion (ROM), the angular displacement, the velocity, the acceleration, and the rate of change of angular acceleration within the normal limits of kinematics expected for the task at each time frame. The upper and lower bounds of these constraints were *a priori* and were estimated in Phase I.

(2) To evaluate each body position that fits in the physical layout at different time frames. One of the basic considerations of the model was collision. As a general rule, the container was not allowed to hit the workstation.

(3) To evaluate the stabilization of the whole body. Townsend's model (1981) retained all of the intuitive dynamic properties such as the inverted pendulum aspect of human support and effect of foot placement (lateral support point) for stabilization. In sagittal manual lifting, the trajectory center of gravity (C.G.) was retained within the range of foot support.

(4) To estimate the segment forces and joint torques within the strength limits of each joint. Crowninshield (1978) showed that the prediction of optimization was dependent on the given limitation of muscle strength. Stobbe (1982) established the limits of joint torques and hence his strength regression model was adopted in this study. His model provided the basic information needed for simulation – the maximal joint torque under different positions of extension and flexion. In addition, it was easy to apply for different population. For the future development, the ideal joint strength limits should be predicted

for different population under dynamic contractions based on both the joint position and the angular velocity instead of static contractions similar to those of Stobbe (1982).

The constraints sifted out the feasible motion patterns, and then an optimization algorithm was used to detect the best motion pattern. This notion was very important: the feasibility of a generated motion pattern was determined by the constraints set, not by the optimization searching algorithm. The output of the simulation was the motion pattern having the smallest resultant value for the objective function value.

For example, Beckett and Chang's (1968) objective function was to minimize the amount of mechanical work done. Chao and An (1978a) found, among thirty different objective functions, the best optimal criteria for their hand model: (1) the minimization of joint constraint moments, (2) the sum of tendon contractions, and (3) the sum of joint constraint forces, which were valid only if the joint was attempting to produce maximal effort. Since manual lifting is a whole body movement, it was postulated that, in all likelihood, the lifter will determine the lifting trajectory in such a manner as to minimize the following objective function:

$$\text{minimize} \int_T^{t=0} \left[\frac{\tau_1(t)}{S_1[\theta_1(t)]} \right]^2 + \left[\frac{\tau_2(t)}{S_2[\theta_2(t)]} \right]^2$$
$$+ \left[\frac{\tau_3(t)}{S_3[\theta_3(t)]} \right]^2 + \cdots \, dt$$

The objective function was a modification from Pedotti et al. (1978), which was the summation over time of the sum of the square of the ratio of the predicted joint moments to the corresponding joint strength. In the simulation program, the continuous time integral was analyzed into a set of discrete epochs and the integration operation was replaced with summation:

$$\text{minimize} \sum_{t=0}^{T} \left[\frac{t_1(t)}{S_1[\theta_1(t)]} \right]^2 \Delta t + \left[\frac{\tau_2(t)}{S_2[\theta_2(t)]} \right]^2 \Delta t$$
$$+ \left[\frac{\tau_3(t)}{S_s[\theta_3(t)]} \right]^2 + \ldots$$

where $\tau_j(t)$ was the torque about joint j at time, and $S_j[\theta_j(t)]$ is the maximal strength joint j under the angular position $\theta_j(t)$.

The denominators $S_j[\theta_j(t)]$ were considered as the capacities of the joints under different postures, and the numerators $\tau_j(t)$ were considered as work load distributed to the joints. Thus, the minimum was esteemed when the joint moments were distributed to the joints based on their capacities at the specific position – a stronger joint would take more of the work. The ratio between $S_j[\theta_j(t)]$ and $\tau_j(t)$ is called muscular utilization ratio (MUR) (Gagnon and Smyth, 1991). The "square" of the MUR guaranteed the value is always greater than zero, and provided a heavier penalty for any deviation in the minimization process. In addition, this objective function accommodated the conservative notion of human motion mentioned in section 2. Therefore, at any time frame, the biomechanical simulation was considered along with (1) maintaining stable and synchronous movements of various body segments, (2) calculating the summation of reactive forces from the resultant linear accelerations and gravity, and (3) calculating the summation of moments at each joint based on resultant angular

acceleration, the moment arms, and the moment of inertia of related segments.

5. Dynamic programming

There are many possible algorithms that can be used to find the optimal motion patterns. Lee (1988) used dynamic programming – an animation approach. The problem was solved using the "trajectory approximation in state spaces method" (Durling, 1964). Fig. 3 illustrates the basic ideas of such an approach, and the principal notions are delineated by the following steps.

(1) The continuation of time axis was divided into discrete stages.
(2) Given the postures of initial and final stages of a lifting course, each stage was accommodated with all kinds of postures, feasible and infeasible. Each posture was called a candidate at the specific stage. Therefore, from the second stage to the penultimate (next to last) stage, each stage had many candidates.
(3) When two candidates from two stages were connected, the angular velocity of every joint was estimated by $\dot{\theta}(k) = [\theta(k) - \theta(k-1)]/$
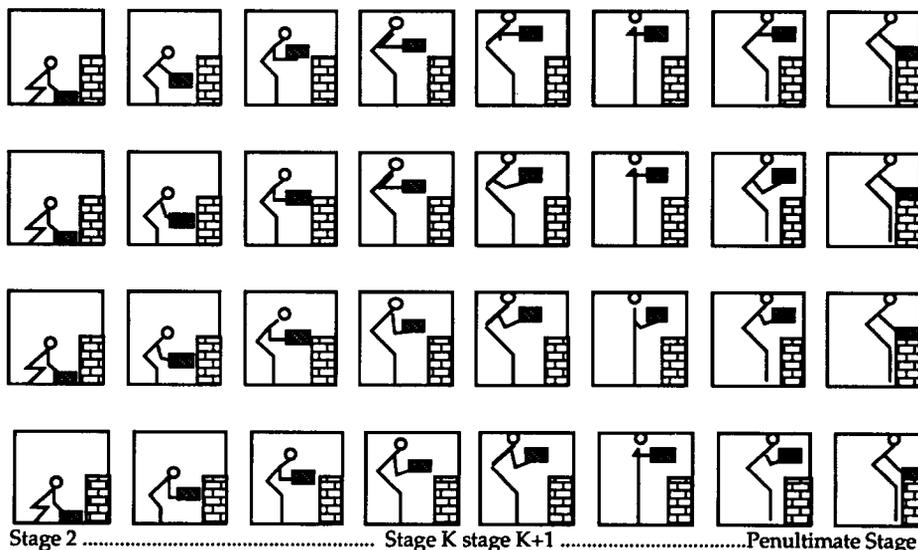

Stage 2 .... Stage K stage K+1 ....Penultimate Stage

Fig. 3. Dynamic programming – a cartoon animation approach.

Table 1
Data structure used in the dynamic programming approach

** structure	
{	
stage	/* the index number of the stage*/
candidate	/* the index number of the candidate */
theta[1]	/* the angular position of joint 1 */
theta[2]	/* the angular position of joint 2 */
theta[3]	/* the angular position of joint 3 */
theta[4]	/* the angular position of joint 4 */
theta[5]	/* the angular position of joint 5 */
objective	/* the least objective function value */
link[stage]	/* the index of candidate of the
[candidate]	previous stage which serves the least objective function value */
}	

Δt, where Δt was the time between the two stages, and k was the stage number. In like manner, the angular acceleration and the rate of change of angular acceleration were estimated.

(4) Based on the kinematics, the kinetics were calculated.

(5) A linked-list data structure was assigned to each candidate to describe the posture and the dynamic of the current candidate while connecting with other candidates from previous stages (Table 1).

By linking different candidates at every stage together, different motion patterns (to accomplish the task) were generated and evaluated by the constraints set. Furthermore, the value of objective function was accumulated and recorded. At the end, the optimal motion pattern was found from the contemporary group of postures. This whole process was referred to as an iteration.

Two strategies were used to generate postures for the new iteration: (1) variation of the optimal motion pattern from previous iteration, or (2) simply generate another group of postures. The drawback of the dynamic programming approach was that the quality of the simulations was highly dependent on the quantity and quality of the postures generated. On the other hand, more candidates or more iterations did not promise improvement of the final result.

6. Expression of displacement-time information and non-linear programming

The key information in biomechanical modeling was the angular displacement. With the information of the angular displacement, the analysis of finite difference was applied to get the information of velocity and acceleration. Then, based on the assumption of the rigid body links and the estimations of the mass, the C.G., the ratio of moment of inertia of each body segment, all kinds of dynamic measures were calculated, such as the joint forces, torques, power, and work done. In essence, this angular displacement-oriented discussion provides a step-by-step strategy for biomechanical simulation of manual lifting:

(1) Find a smooth and differentiable function to express angular displacement.

(2) Use five such functions to express the displacement of five selected joints (elbow, shoulder, hip, knee, and ankle). When any of the limited parameters of function change, the motion pattern of the angular displacement changes.

(3) Use those functions to formulate the kinematic constraints by applying their derivatives, and to formulate the physical and kinetic constraints by combining anthropometric inputs and kinematic information.

(4) Plug the whole formulation of the previous step into an optimization algorithm. Then, the algorithm finds the optimal parameters for each of the angular displacement functions, and the resulting manual lifting trajectory will not only satisfy all the constraints but will also provide the smallest objective function value.

In order to apply the above strategy in biomechanical simulation, there are two major parts in this section: (1) introduction of the mathematical expression, and (2) introduction of the optimization algorithms. Slote and Stone (1963) used this relationship

$$\theta(t) = \frac{D}{2\pi}\left[\frac{2\pi t}{T} - \sin\left(\frac{2\pi t}{T}\right)\right]$$

to describe forearm flexion, where D was the maximal angular displacement, and T was the

total time of the movement. Muth (1976) applied their formula and Chebshev polynomials to approximate displacement-time information, and optimization which was based on a projected gradient modification of variable metric descent. Muth's work propounded the idea of using mathematical expressions to describe angular displacement. In fact, any curve fitting techniques adequate for smoothing can be used to express the continuous and differentiable motion patterns, such as polynomial, harmonics, and spline curves (Hamming, 1989). In this 5-joint lifting study, it was assumed that an eighth order polynomial was sufficient to represent the angular displacement of each joint j:

$$\theta_j(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$
$$+ a_6 t^6 + a_7 t^7 + a_8 t^8,$$

where $0 \le t \le T$.

It was obvious that there were nine coefficients $a_0, a_1, a_2 \ldots a_3$ required to be solved. These nine coefficients determine how the joint moves. Now consider that the initial position θ_{I_j} and final position θ_{F_j} were given, and the initial angular velocity, the final angular velocity, and the final angular acceleration were assumed to be zero. The following five equations were formulated:

$$\theta_j(0) = a_0 = \theta_{I_j}$$

$$\theta_j(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5$$
$$+ a_6 T^6 + a_7 T^7 + a_8 T^8 = \theta_{F_j}$$

$$\dot{\theta}_j(0) = \frac{d\theta_j(t)}{dt}\bigg|_{t=0} = a_1 = 0$$

$$\dot{\theta}_j(T) = \frac{d\theta_j(t)}{dt}\bigg|_{t=T}$$
$$= a_1 + 2a_2 T + 3a_3 T^2 + 4a_4 T^3 + 5a_5 T^4$$
$$+ 6a_t T^5 + 7a_7 T^6 + 8a_8 T^7 = 0$$

$$\ddot{\theta}_j(T) = \frac{d\dot{\theta}_j(t)}{dt}\bigg|_{t=T}$$
$$= 2a_2 + 6a_3 T + 12a_4 T^2 + 20a_5 T^3$$
$$+ 30a_6 T^4 + 42a_7 T^5 + 56a_8 T^6 = 0$$

Still, these five equations were only good enough to solve five coefficients; the other four coefficients were undetermined. Thus, four degrees of freedom of each joint were designated for the optimization $(9 - 5 = 4)$. Certainly, if another assumption was made, such as the rate of change of angular acceleration at the end of the lifting course being equal to zero, then:

$$\dddot{\theta}(T) = \frac{d\ddot{\theta}_j(t)}{dt}\bigg|_{t=T} = 6a_3 + 24a_4 T + 60a_5 T^2$$
$$+ 120a_6 T^3 + 210a_7 T^4$$
$$+ 336a_8 T^5 = 0,$$

and the degrees of freedom would have been automatically reduced from four to three. Thus, between simplicity and reality, one had to find a trade-off point in settling the dispersion of the degrees of freedom:

$$DF(M) - DF(A) = DF(O)$$

where:

DF(M) – degrees of freedom included in the model;

DF(A) – degrees of freedom used in making assumptions;

DF(O) – degrees of freedom used for the optimization.

In fact, the above deliberation was not only due to the Principle of Parsimony (Occam's Razor) but also due to the consideration of computation speed and memory space limitation of simulation hardware. After the mathematical expressions for the angular displacements including function type and degrees of freedom dispersion were decided, an optimization algorithm was applied to provide the final solution of all the coefficients based on the objective function and constraints. Hardt (1978) noticed that the optimization provides unrealistic behavior and this may be partly due to the inherent limitation imposed by the linear programming algorithm he used. Thus, non-linear programming algorithms using gradient as the searching direction were applied by some researchers. For example, Crowninshield and Brand (1981) used the Rosen Gradient Projection algorithm. Davy and Audu (1987) used the Flectcher-Reeves conjugate gra-

dient algorithm to solve the dynamic optimization and the Gradient-restoration algorithm to solve the static optimization. In this 5-joint lifting study, the General Reduced Gradient (GRG) algorithm (Lasdon et al., 1978) was used. Since the searching algorithm serves as a tool to find the motion pattern with the minimal objective function value, there was no intention in this paper to further discuss Lasdon's GRG algorithm. The following exegesis reveals some rudiments of how the displacement-time information was synthesized by GRG:

(1) Variables definition – The first step was to define the variables involved in the problem. In the case of motion optimization, the variables were the coefficients of the polynomials that were used to describe the angular displacements $\theta_j(t)$. The kinematic constraints for $\dot{\theta}_j(t)$, $\ddot{\theta}_j(t)$, and $\dddot{\theta}_j(t)$ were formulated according to the polynomials. Furthermore, the constraints related to physical layout and the kinetic constraints, such as $\tau_j(t)$ were calculated based on $\dot{\theta}_j(t)$ and the parameters of body segment length, weight, and moment of inertia discussed in the previous section. Finally, both numerators $\tau_j(t)$ and denomina-

tors $S_j[\theta_j(t)]$ in the objective function were also a function of $\theta_j(t)$, and $\ddot{\theta}_j(t)$.

(2) Variables partition – The variables were partitioned into dependent and independent variables. The values of the dependent variables were implicitly determined by the values of the independent variables. Partitioning was important to make the objective function a function of only independent variables in order to reduce the problem size and to increase efficiency of the search for optimum.

(3) Solution initialization – All the coefficients for the polynomial were set to zero at the beginning, which was an infeasible solution. At this point, some of the coefficients of the polynomials were either increased or decreased to improve the value of the objective function. The amount and direction of this increase or decrease were provided by GRG.

(4) Direction computation – The direction of improvement of the objective function was determined by Wolfe's reduced gradient method. The directions were applied either to increase or to decrease the value of the independent variables. An independent variable was feasible for direction computation if the
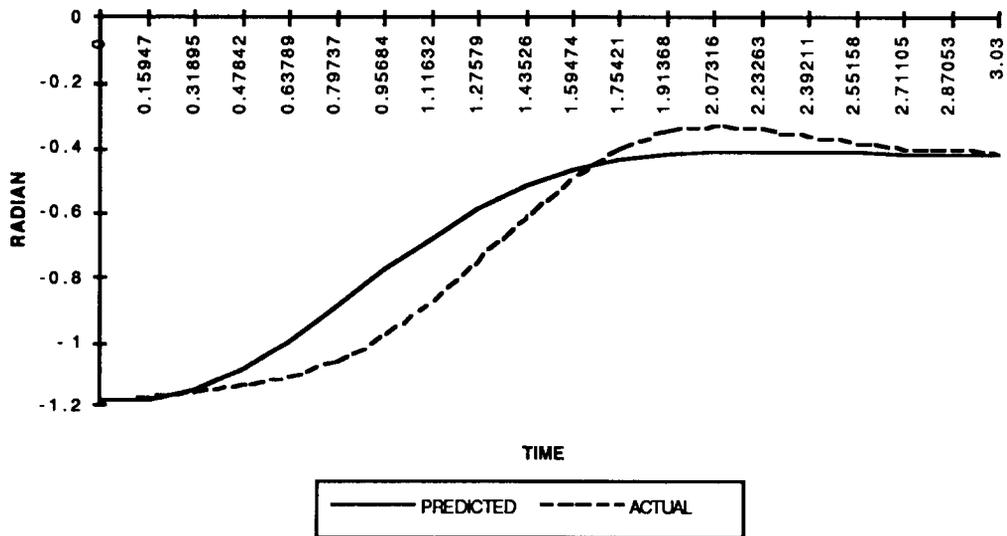

Fig. 4. Comparison between the predicted and the actual motion patterns of the elbow joint during the course of lifting.
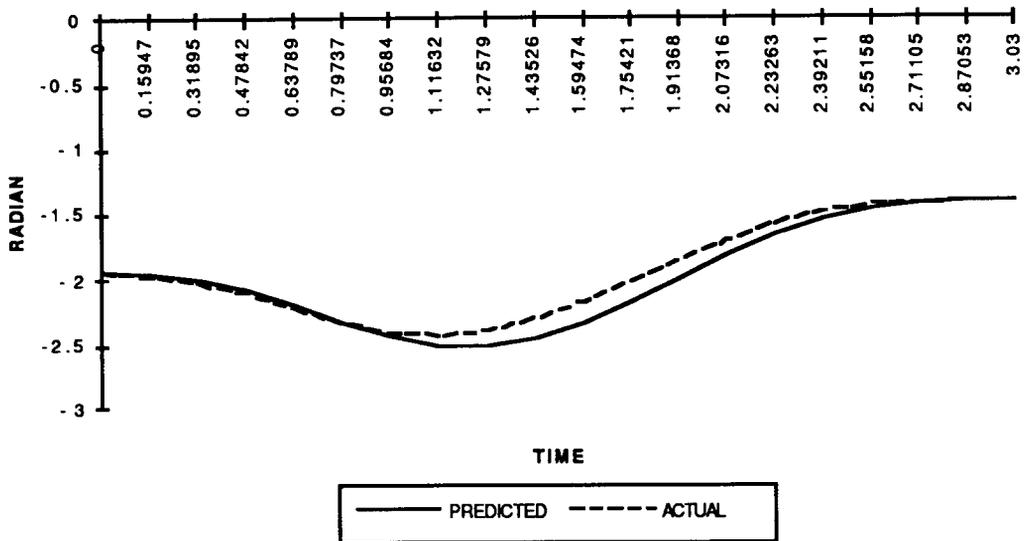
Fig. 5. Comparison between the predicted and the actual motion patterns of the shoulder joint during the course of lifting.

value derived based on the constraints set was within the upper and lower bounds. The direction was determined by the reduced gradient, which was a vector pointing toward the optimal solution.

(5) Pivoting – An independent variable was changed into a dependent variable by assign-

ing a value, and a dependent variable was increased to a constraint upper bound or else decreased to a constraint lower bound.

Figs. 4–8 illustrate the comparison between the actual and predicted motion patterns for angular displacement of the elbow, shoulder, hip, knee, and ankle for a lifting task.
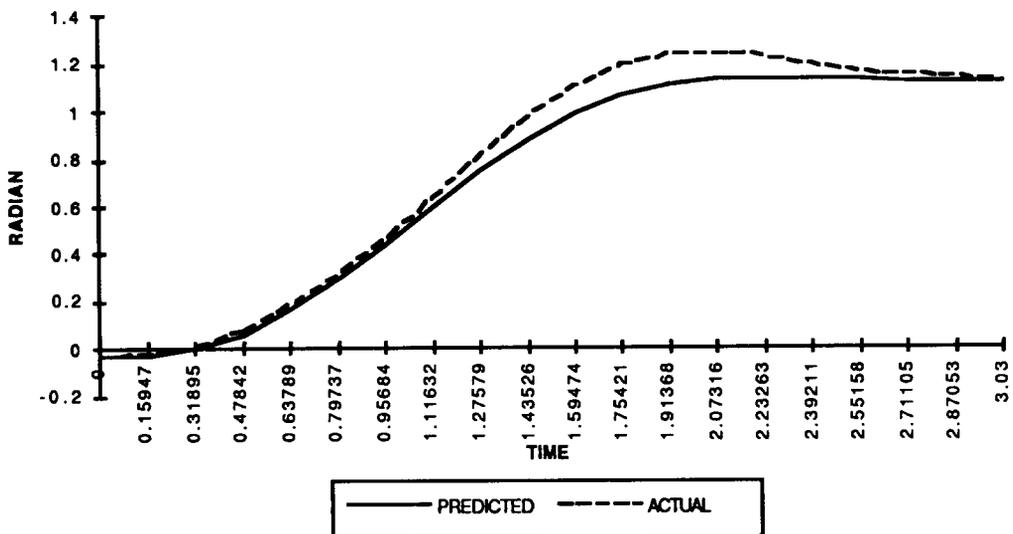
Fig. 6. Comparison between the predicted and the actual motion patterns of the hip joint during the course of lifting.
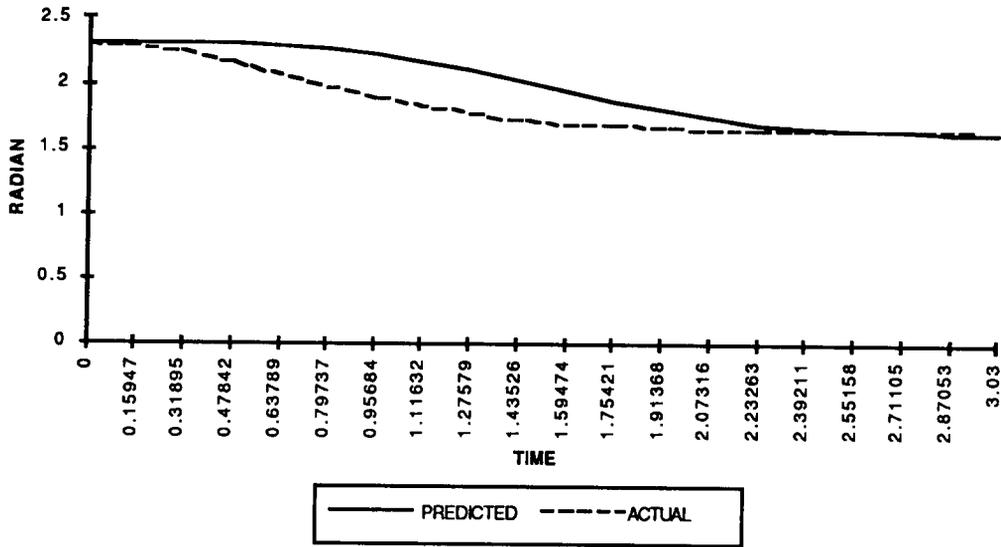
Fig. 7. Comparison between the predicted and the actual motion patterns of the knee joint during the course of lifting.

7. Results and discussion

Biomechanical simulation, in nature, was simply the generation of the information about how the body moves from an initial posture to a final posture to accomplish a manual task. The main issue in this paper was the development of the methodology of such a simulation. This paper demonstrates how to systematically identify all the required components for a biomechanical simulation, how to generate motion patterns by the assumptions and mathematical expressions, how to examine motion patterns' feasibility by the constraints set, and how to select an optimal motion pattern.

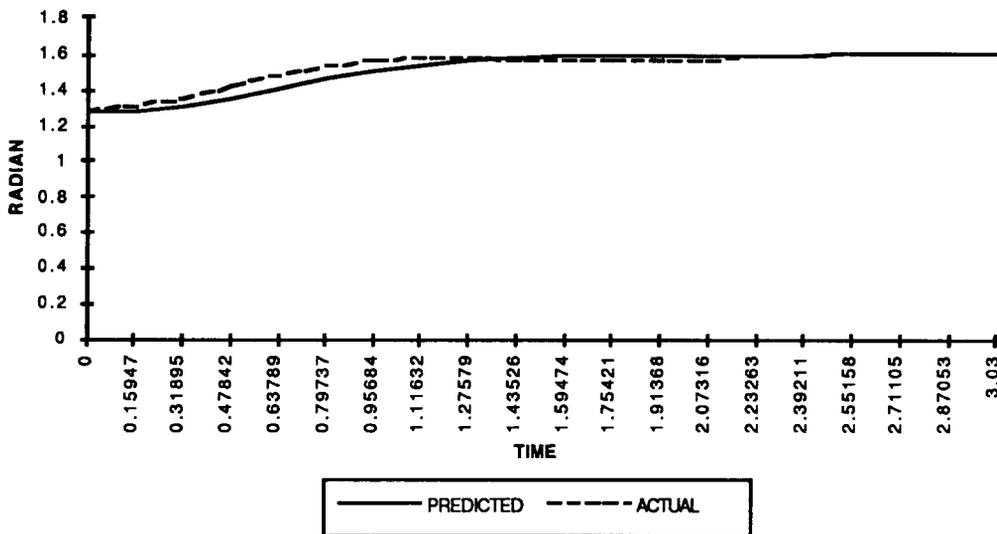Such a simulation program must predict the

Fig. 8. Comparison between the predicted and the actual motion patterns of the ankle joint during the course of lifting.

selected joints' position at any given time frame. In this simulation program of manual lifting, there was no restriction on the initial posture or the lifting style. That is, the initial posture could be stoop, squat, or any feasible posture, and the lifting style was not restricted to leg lift, back lift, or any specific lifting style. The significant contribution of this described technique is the synthesis of the motion pattern of manual lifting by integrating the assumptions of human body (similar to biomechanical modeling), the observations of human behavior, and the application of optimization of techniques to the body. Technically, it provides the whole body moving strategy based on the consideration of stabilization, the avoidance of collision, the magnitude of joint kinematic, and the strength. The major advantage of such a method was ability to describe the mechanical consequences of performing a physical task dynamically without evoking the optimization of the distribution of the muscular efforts. The simulation can be applied at a skeletal level without concerning the discrepancy between the net reaction at body joint and the internal forces (e.g., muscular force, force due to intra-abdominal pressure) that produce the net reaction described by Schultz et al. (1981, 1982, 1983).

Because most of the observed actual motion patterns in this study were not optimal, one may want to understand two major questions: (1) How much difference can be observed between the predicted and the actual motion patterns? (2) What may be causes of these differences? Hatze (1976) found that any motion of the bio-system which deviates from the predicted optimal one takes a longer time to complete and was thus not optimal. Since the time to accomplish the lift was a given input, Hatze's conclusion cannot be applied in this paper. Since the time cannot be used as an evaluation tool, in order to compare the predicted motion patterns with the actual pattern two evaluation tools were developed:

(1) Sum of squares – the measure due to the geometric distance between the predicted motion pattern $P(t)$ and the corresponding actual motion pattern $A(t)$.

(2) Number of concordant and discordant pairs – the measure of the agreement between $P(t)$

Table 2
Average performance of model prediction versus actual motion patterns based on the evaluation tools: sum of squares and number of disconcordant pairs

	Elbow	Shoulder	Hip	Knee	Ankle
	Average sum of squares				
Subject					
1	1.41	1.29	0.17	0.12	0.07
2	0.48	4.37	0.58	0.18	0.29
3	0.61	2.48	0.52	0.47	0.14
4	0.43	2.85	0.36	0.12	0.15
	Average disconcordant pairs				
Subject					
1	4.06	2.56	1.75	2.06	5.69
2	5.75	4.44	3.13	1.75	8.88
3	4.69	5.75	3.13	2.25	7.75
4	4.80	3.80	1.93	0.80	8.73
	Average sum of squares				
Size [a]					
A	0.87	2.72	0.43	0.12	0.14
B	0.60	2.78	0.38	0.33	0.19
	Average of disconcordant pairs				
Size [a]					
A	4.69	4.09	2.22	1.63	7.81
B	4.97	4.19	2.77	1.84	7.68
	Average sum of squares				
Range [b]					
K	0.28	2.31	0.58	0.21	0.18
S	1.21	3.20	0.23	0.24	0.15
	Average of disconcordant pairs				
Range [b]					
K	5.94	3.91	3.22	2.56	7.06
S	3.68	4.39	1.74	0.87	8.45

[a] Comparisons between container sizes
[b] Comparisons between lifting ranges

and $A(t)$. When $P(t)$ and $A(t)$ were increasing or decreasing from t to $t+1$, the relationship between the two was defined as concordance. Otherwise, $P(t)$ and $A(t)$ were discordant.

Table 2 shows the average performance of the model prediction versus the actual motion patterns from the final validation based on the two evaluation tools. For example, for subject 1, the average (over 4 repetitions) sum of squares of

elbow joint was 1.41 rad^2 (when each repetition was equally divided 20 stages), and there were in average 4.06 disconcordant pairs. Descriptively, the small values of the average sum of squares show that the predicted and the actual motion patterns were very close to each other, and the numbers of disconcordant pairs indicate that there was a phase shift between the predicted and the actual motion patterns. That is, the two motion patterns may follow pretty much the same magnitude of motion; however, the timing to decide to change from flexion to extension (or vice versa) was not at the same pace (Figs. 4–8). Several attempts to reduce such a phase shifting in this research are currently being considered. It was evident that the performance of certain joints from some subjects was closer to the optimal pattern in some tasks. The following is an anecdotal summary based on the comparison of the four subjects in the validation phase:

(1) The average of sum of squares from the ankle joint was usually very small. The large numbers of the average disconcordant pairs were due to the very small magnitude oscillation of the angular displacement after the subject stands up (Fig. 8). Though the oscillation in the actual motion pattern can be noticed when compared with the prediction, the purpose of such oscillation in the actual motion pattern was not clear.

(2) The shoulder joint had the highest value on the average sum of squares and disconcordant pairs based on the comparison of the angular displacement. The abduction and adduction of the shoulder joint, which was not considered in the model, may be the cause.

(3) The actual trunk, including pelvis, was continuously changing the combination of contours between the lordotic and kyphotic curvatures during the course of motion. The model was not capable of describing such a deviation, and the deviation was compensated by the flexion and extension of the shoulder and hip joints.

(4) There was no observable difference, using either of the two evaluation tools, between different container sizes and between different lifting ranges.

(5) The model prediction tends to move the container closer to the body, and the actual motion patterns higher above the workstation before lowering the container on the workstation. Lee (1988) explained that such a disagreement was due to the subjects' perception difference. Such a psychological effect for the requirement of body-container-workstation clearance causes the actual motion patterns to deviate from the optimal.

(6) Another example of non-optimal behaviors was that the actual motion patterns show that most subjects tend to stand up faster than the model prediction. Grieve (1975), Freivalds et al. (1984), and Danz (1990) reported that moments of the trunk reached a peak shortly after the initiation of the lift, when a maximal upward acceleration coincides with a disadvantageous position of the body and load. Such a consideration was not designed in the current version of the simulation model. Furthermore, one subject explained his body movement and coordination after the experiment, saying that his fast stand-up was a strategy to prevent the edge of the container hitting the tibia, another subject explained he tried to generate enough force at the beginning of the lift to overcome the inertia. This speculation was also useful in explaining the phase shifting discussed previously.

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