EVALUATION OF GRIP FORCE EXERTIONS IN DYNAMIC MANUAL WORK

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ABSTRACT

An obstacle to the development of guidelines for reducing forceful hand movements is that manual force is not easily measured or estimated at the worksite, especially during highly dynamic activities. Grip force requirements during manual work are dependent not only on object weight, but also on the surface characteristics of the object and the task dynamics. In theory, it is possible to predict grip force requirements for manual tasks using Newtonian laws of physics; however few researchers have attempted to measure grip force during dynamic work, much less to compare actual grip force values to predicted levels. Therefore, a laboratory experiment was conducted to examine grip force exertions during two simulated industrial tasks. In each task, participants repetitively grasped and moved aluminum handles against varying levels of weight or resistance. Grip force was measured using a strain gauge mounted inside the handles. Results indicate that grip force varied continuously throughout each work cycle in response to changes in the motion of the hand/handle. The pattern of variation was consistent between subjects and could be approximated by a sinusoidal model. Greater interindividual variation in grip force exertion was observed when the task allowed greater flexibility in selecting a movement strategy. The results also indicate that subjects are more likely to "overshoot" the necessary grip force (i.e., apply more force than needed) at the initiation of movement, especially at lower weight levels. This study demonstrates that it is possible to predict variations in grip force during dynamic work, although further refinements in the procedure are needed. Use of modelling techniques will enable industrial designers to better estimate grip force requirements and to identify design strategies that will reduce the risk of musculoskeletal injury to the worker.

INTRODUCTION

Many industrial tasks require workers to exert forces with the hands and fingers to grasp or manipulate objects. At the same time, it is increasingly recognized that forceful hand exertions are a potential cause of chronic musculoskeletal disorders (Putz-Anderson, 1988). The magnitude of the risk to the American workforce is at least partially revealed by data collected during the National Occupational Exposure Survey (NOES) of 1981-1983. During this survey, arm-transport movements (i.e., using the arms to move small or light objects from one position to another) and hand/wrist manipulations were among the ergonomic hazards most frequently identified by NOES surveyors (Winn, 1990).

Because of difficulties in directly measuring the force applied during manual work, it is not uncommon for researchers to estimate the manual force requirements of a given task based on external task parameters. For example, the weight of hand-held tools or objects is often used as a surrogate for direct force measurements in ergonomic worksite assessments (Keyserling, Armstrong and Punnett, 1991). A weakness of this approach is that other factors, including the surface characteristics of the object and the task dynamics, can greatly influence grip force requirements during manual transport tasks.

One type of hand exertion commonly found in industry is the grasping of a vertically-oriented handle or object, such as a vertical screwdriver. For *static* holding tasks, the force required to prevent a hand-held object of mass (m) from slipping out of the hand (F_{hand}) can be determined using Newton's Second Law of Motion:

$$F_{hand} - mg = 0 \qquad (1)$$

$$F_{hand} = mg \qquad (2)$$

where g is the acceleration due to gravity (9.81 m/s^2).

Because F_{hand} is a frictional force, it is equal to the product of the coefficient of static friction between the skin and the surface of the object being held (μ), and the force applied normal to the surface of the object, i.e., the grip force.

$$F_{hand} = \mu F_{grip} \qquad (3)$$

Therefore, the required grip force for a static holding task can be determined using the following relationship:

$$F_{grip} = mg/\mu \quad (4)$$

For *dynamic* tasks, in which hand-held objects are moved over a given distance, grip force requirements are not constant, but vary as a function of the vertical acceleration of the hand/handle (a_y). To initiate movement, the vertical force applied to the mass by the hand must be greater than the force of gravity acting on the mass (mg).

$$F_{hand} - mg = ma_y \quad (5)$$

$$\mu F_{grip} - mg = ma_y \quad (6)$$

$$F_{grip} = m(a_y + g)/\mu \quad (7)$$

It has been shown that the motion of the hand during transport movements can be treated as a two-dimensional motion performed in a plane oriented in accordance with the direction of motion (Kuttan and Nadler, 1969). If the path of hand motion can be described, the acceleration of the hand (a_y) can be determined through differentiation. Using this information with data concerning the frictional characteristics of various materials against human palmar skin (Westling and Johansson, 1984; Buchholz, Frederick and Armstrong, 1988), solution of equation (7) for F_{grip} is possible. Nonetheless, few researchers have attempted to measure grip force during dynamic work, much less compare actual grip force values to predicted levels. As a result, the extent to which grip force is optimized during dynamic work (i.e, that actual force values match required force values) is largely unknown. Therefore, a laboratory experiment was conducted to examine grip force exertions in two simulated industrial tasks.

METHODS

Subjects

Thirty right-handed males between the ages of 18 and 30 years were recruited from a temporary employment agency to perform one of two manual tasks (15 subjects per task). All participants were free of known musculoskeletal impairments. Prior to each test session, informed consent was obtained and anatomic measurements of the hand and arm were made. All procedures were approved by the NIOSH Human Subjects Review Board (HSRB).

Experimental Tasks

The tasks and the associated work stations used in this experiment have been previously described in Grant et al. (1992) and Grant and Habes (1993). Briefly, two work tasks were devised to simulate common activities in industry. In the first task (material transfer task), fifteen seated participants grasped and lifted a cylindrical aluminum handle (Figure 1a) from a location on the right side of a circular platform to a receptacle 42 cm away on the left side of the platform (a movement in two dimensions). In the second task (assembly task), fifteen seated participants grasped and pulled downward on the same handle, suspended 43 cm above the workstation on a rope which passed over a pulley (Figure 1b). A weight-loaded canister tied to the other end of the rope provided rope tension as the handle was pulled downward. After pulling the handle to a target affixed to the top of the workstation, participants paused briefly and returned the handle to its original position (essentially a one-dimensional motion). Each task was performed using a power grip, against three levels of weight (0.65 kg, 1.1 kg, and 2.1 kg in the material transfer task, and 1.1 kg, 2.3 kg, and 3.4 kg in the assembly task). The equipment design allowed investigators to change the weight without the knowledge of the participants or a change in the appearance of the task. Each participant performed one 2.5 minute trial at each weight. During each trial, participants initiated movement of the tool handle once every five seconds. A three minute rest period was provided after each trial to minimize the influence of fatigue. Participants were instructed to perform each task in a smooth manner, without rapid or sudden movements. Participants were also allowed to practice the task before data collection commenced.

Grip Force Measurement

The grip force applied to the handle was monitored continuously using a strain gauge mounted in the handle. The configuration used to mount the strain gauge is described by Pronk and Niesing (1981). Power and amplification for the strain gauge was provided by a Force Monitor© (Prototype Design, Ann Arbor, MI). Because of an instrumentation problem (overamplification of the signal by the Force Monitor©) useable force data were obtained from 12 of the 15 participants in the first task, and 9 of the 15 participants in the second task.

To facilitate data analysis, a switching circuit was set up so that a +5 VDC signal was presented to the computer whenever the participant grasped and moved the handle. Both channels of data (strain gauge and switching circuit) were sampled at 175 Hz

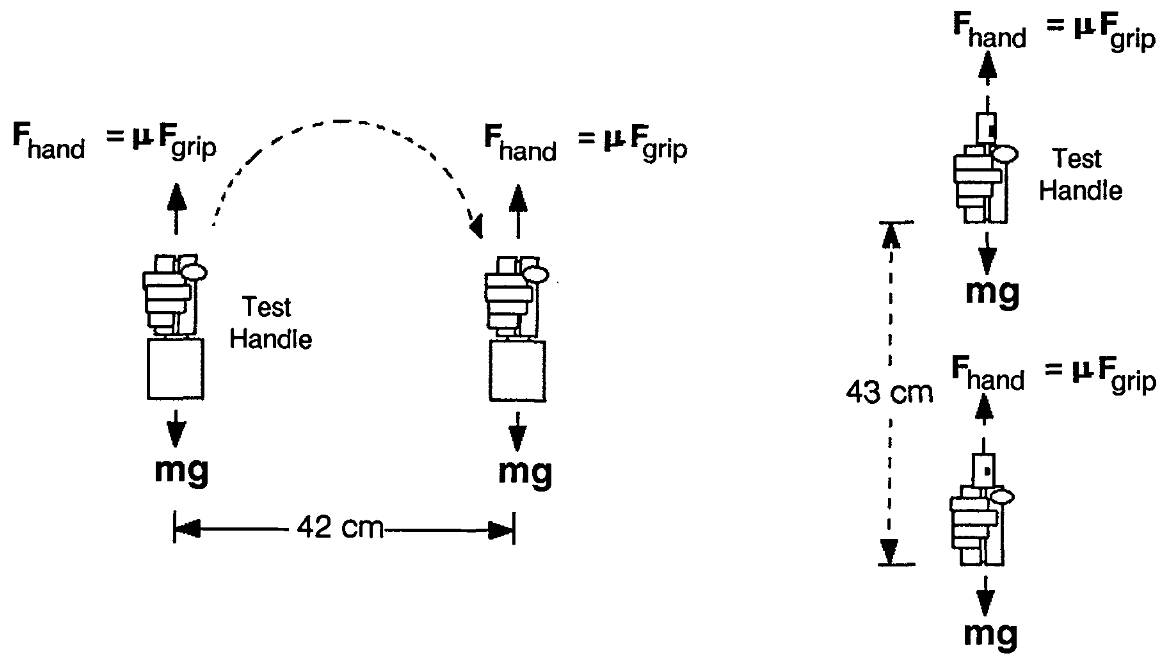

Figure 1. Forces (arrows) and movement paths (dashed lines) for (a) material transfer task, and (b) assembly task.

using a 12-bit analog-to-digital converter and LabTech Notebook© data acquisition software. Data were stored in binary form using a Compaq 286 microcomputer. Software developed for this experiment was used to score the grip force data in relation to the motion periods defined by the switching circuit. To account for small variations in movement time between subjects and conditions, movement time was normalized, i.e., time is expressed as a percentage of the work cycle.

Grip Force Prediction

Grip force requirements for each task were calculated assuming that the vertical position, velocity and acceleration of the hand could be described by a sinusoidal model. It has been demonstrated that the path of hand motion during voluntary arm movements can be described by a sinusoid (Nadler and Goldman, 1963; Slote and Stone, 1963; Ayoub, 1966). Although there is evidence that a sinusoidal model does not provide the best description of hand motion during transport tasks (Ayoub, Ayoub and Walvekar, 1974), it does provide a reasonable starting point for investigators wishing to estimate hand forces without making complex measurements of hand motion. For the manual transfer task, it was assumed that $a_y(t)$, the vertical acceleration of the hand as a function of time (t), could be described by the following:

$$a_y(t) = Y_{Max}(2\pi/T)^2\cos(2\pi t/T) \quad (8)$$

where Y_{Max} = the maximum distance the hand travels in the y-direction from the starting point (assumed to be 19 cm, half the average distance between shoulder and elbow height) and T = the total motion time (measured to be 1.31 sec).

For the assembly task, a piecewise approach was used, since the task was comprised of two separate motions (downward motion of the hand to pull the handle to the workstation, upward motion of the hand to return the handle to its original position):

$$a_y(t) = -Y_{Max}(2\pi/T^2)\sin(2\pi t/T) \quad (9)$$

$$a_y(t) = Y_{Max}(2\pi/T^2)\sin(2\pi t/T) \quad (10)$$

where Y_{Max} = 43 cm and T = 1 sec (each motion).

By substituting (8) (9), and (10) into (7), grip force requirements for each task, as a function of time, can be estimated. Through differentiation and integration of the equations, peak and mean hand forces can also be assessed. In this study, the equations indicate that peak values should exceed mean levels by 44.6% in the manual transport task, and 27.3% in the assembly task. The equations also indicate that grip force values are expected to peak at or near the beginning of each task (as the hand force overcomes the inertia of the handle to initiate movement) and at the end of the cycle (as the hand force acts to brake the motion of the handle). Finally, the equations reveal that while Y_{Max} and T both affect the magnitude of grip force requirements, only T affects the pattern of variation in grip force (i.e., the ratio of peak-to-mean force).

RESULTS

Grip force profiles for subjects performing the material transfer task and the assembly task are shown in Figures 2a and 2b. Average grip force is plotted as a function of time within the work cycle (0 = start of movement, 1 = end of movement).

As shown, grip force varied continuously throughout the work cycle, indicating that participants adjusted the force applied to the handle in response to changes in the motion of the handle. As predicted, peak grip force values coincided with initiation of handle movement. Peak grip force levels exceeded mean values by as much as 104% (transfer task) and 114% (assembly task); however the ratio of peak-to-mean force declined significantly with increased object weight/resistance ($p < 0.01$ for both tasks). Because the peak almost always occurred at the initiation of movement, this finding indicates that participants tended to "overgrip" at the initiation of all movements, and that this tendency is exaggerated at lower weight levels.

Although the force-time curves show definite sinusoidal characteristics, the patterns differ substantially from those initially hypothesized. In the manual transport task, while the curves display two distinct peaks, the peaks are not of equal magnitude, indicating that movements were not perfectly "smooth," or that participants tend to overgrip at the initiation of movement. In the assembly task, although two distinct sinusoidal patterns are present, they are not of equal magnitude. Nonetheless, the hypothesized models did provide reasonably close estimates of the peak grip forces exerted by subjects during performance of the task. In the manual transport task, the peak grip force actually exerted by subjects differed from that predicted by the model by an average of +8% (at 0.65 kg), +1.1% (at 1.1 kg) and -22% (at 2.1 kg). In the assembly task, the difference between actual and predicted peak forces averaged +12.9% (at 1.2 kg), +13.6% (at 2.2 kg) and -18.2% (at 3.4 kg).

Between-subject comparisons of grip force profiles indicated that the pattern of variation in grip force was remarkably similar between subjects performing the same task. After normalizing grip force profiles from different subjects to a standard work period length, grip force values at various points in the work cycle were matched and compared across subjects. Correlation analysis yielded Pearson product-moment coefficients ranging from 0.42 to 0.99 for participants in the manual transfer task, and from 0.85 to 1.0 for participants in the assembly task. It is notable that greater interindividual variation in grip force pattern and exertion level was observed during the material transfer task, since the transfer task allowed participants greater flexibility in selecting a movement strategy. In the assembly task, vertical movement distance (Y_{max}) was fixed at 43 cm. In the material transfer task, the only requirement was that the handle had to be lifted high enough to clear the edge of the receptacle. While previous research indicates that participants optimize their path of motion to minimize the total power

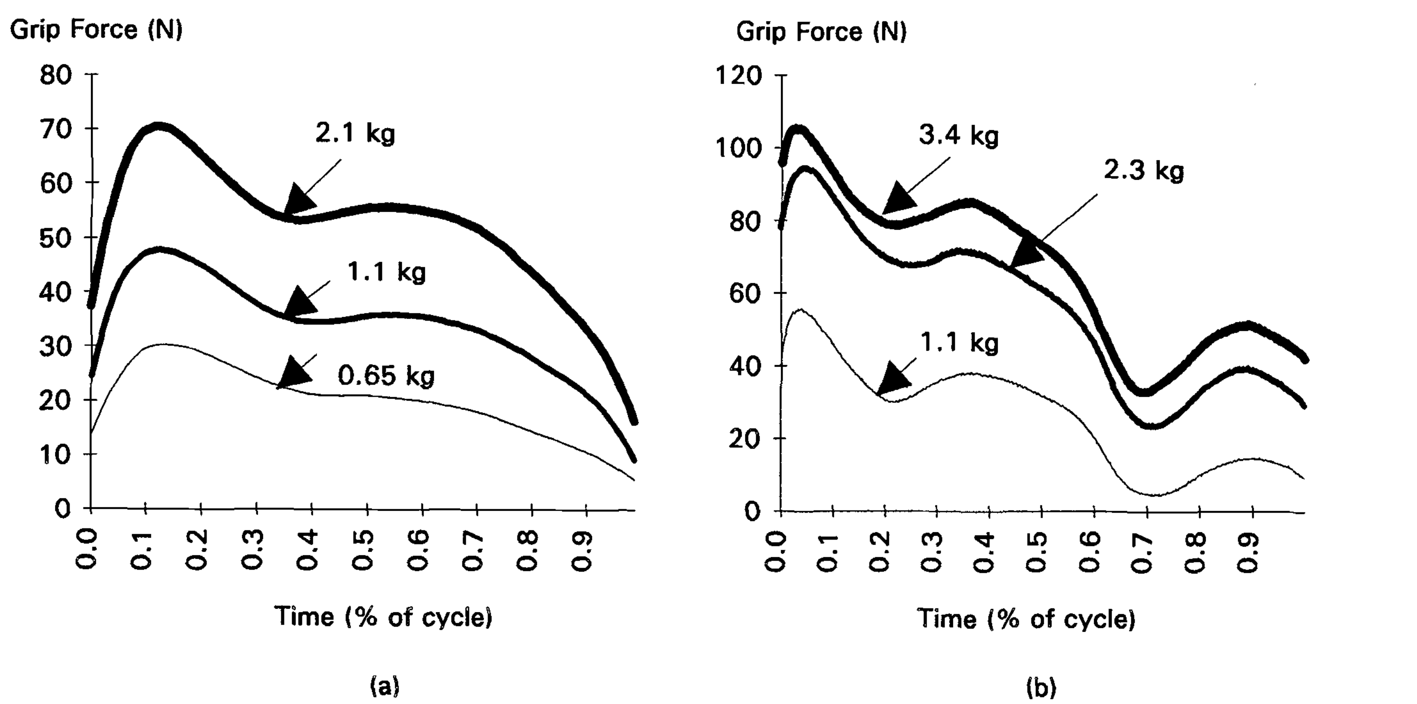

Figure 2. Normalized grip force profile for subjects performing (a) material transport task, and (b) assembly task.

required for the motion, variation in motion between individuals (due to anthropometric differences) is expected (Ayoub et al., 1974).

DISCUSSION

This study demonstrates that human grip force exertion varies consistently in response to changes in grip force requirements during dynamic manual tasks. Furthermore, it demonstrates that peak grip force levels during simple manual activities can significantly exceed mean levels, or levels predicted from static analyses of grip force requirements. Because peak exertion may be more related to the risk of muscle fatigue and hand injury than mean exertion, epidemiological studies which substitute estimates based on object or tool weight for actual grip force measurements may be subject to substantial bias. The dynamic model assumed for this study provided an improved estimate of peak grip forces, although the pattern of exertion deviated substantially from that predicted by the simple sinusoidal model adopted at the outset of the analysis. Whether differences are due to the fact that a more accurate model of hand motion is required, or that humans fail to optimize the amount of grip force applied to perform a given task (i.e., they apply more force than is needed to prevent slipping) remains to be determined. One advantage to the simple model used in this study, however, is that it uses easily measured task parameters (i.e., movement time and distance) as input. The results of this study indicate it is possible to construct models to accurately predict grip force requirements during dynamic tasks, although further refinements are needed to improve the correlation between predicted and observed forces during complex movements (e.g., coupling the grip force model to improved models for predicting hand motion). Use of these models will enable industrial designers to better estimate grip force requirements and to identify design strategies that will reduce the risk of musculoskeletal injury to the worker.

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REFERENCES

Ayoub, M.M. (1966). Effect of weight and distance travelled on body member acceleration and velocity for three-dimensional moves. International Journal of Production Research, 5(1), 3-21.

Ayoub, M.A., Ayoub, M.M., and Walvekar, A.G. (1974). A biomechanical model for the upper extremity using optimization techniques. Human Factors, 16(6), 585-594.

Buchholz, B., Frederick, L.J., and Armstrong, T.J. (1988). An investigation of human palmar skin friction and the effects of materials, pinch force and moisture. Ergonomics, 31, 317-325.

Grant, K.A., and Habes, D.J. (1993). Effectiveness of a handle flange for reducing manual effort during hand tool use. International Journal of Industrial Ergonomics, 12(3), 199-207.

Grant, K.A., Habes, D.J., and Steward, L.L. (1992). An analysis of handle designs for reducing manual effort: The influence of grip diameter. International Journal of Industrial Ergonomics, 10(3), 199-206.

Kattan, A., and Nadler, G. (1969). Equations of hand motion path for work space design. Human Factors, 11(2), 123-130.

Keyserling, W.M., Armstrong, T.J., and Punnett, L. (1991). Ergonomic job analysis: a structured approach for identifying risk factors associated with overexertion injuries. Applied Occupational and Environmental Hygiene, 6(5), 353-363.

Nadler, G., and Goldman, J. (1963). Operator performance studies: II. -- Learning analysis from three plane motions. Journal of Industrial Engineering, 14(5), 259.

Pronk, C.N.A., and Niesing, R. (1981). Measuring hand-grip force, using a new application of strain gages. Medical and Biological Engineering and Computing, 19, 127-128.

Putz-Anderson, V. (1988). Cumulative trauma disorders: a manual for musculoskeletal diseases of the upper extremity. Philadelphia: Taylor & Francis.

Slote, L. and Stone G. (1963). Biomechanical power generated by forearm flexion. Human Factors, 5, 443-452.

Westling, G., and Johannson, R.S. (1984). Factors influencing the force control during precision grip. Experimental Brain Research, 53, 277-284.

Winn, F.J. (1990). NOES-based probabilities of exposure to ergonomic hazards and physical agents by two-digit standard industrial classification codes. National Institute for Occupational Safety and Health, Cincinnati, Ohio.