FORCE EXERTION DURING SQUAT LIFTING WITH LIGHT LOADS

by

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F_a = Force transmitted through the arms, pounds

F_{av} = Vertical component of force transmitted through the arms to lift the object, pounds

F_{ah} = Horizontal component of force transmitted through the arms to lift the object, pounds

F_{bv} = Force lifting the body, pounds

F_{rv} = Vertical component of resultant force on the platform, pounds

F_{rh} = Horizontal component of resultant force on the platform, pounds

M_r = Resultant moment on the platform, inch-pounds

W_o = Object weight, pounds

W_b = Body weight, pounds

θ = Angle formed between the arms and a vertical line through the object, degrees

A_o = Acceleration of object, ft/sec^2

A_b = Acceleration of body, ft/sec^2

d = Distance from the locus of applied force to the platform to the center of gravity of the body, inches

h = Height of the center of mass of the object above the platform surface, inches

L = Distance from the center of gravity of the body to center of mass of the object, inches

INTRODUCTION

Man depends on an extensive system of transport. Highly industrialized countries have designed machines which greatly alleviate man's role in lifting and carrying while less developed nations rely on heavy repetitive manual labor.

The superiority of machines over man as a means of transport can be measured in terms of efficiency, economic cost, and maintenance. Many complaints have been voiced about the efficiency of a gasoline engine but in comparison the human body is extremely inefficient. The price of food, which provides energy for the body, is high and according to the International Occupational Safety and Health Information Centre (1962) "electric or gasoline-driven motors are over a hundred times cheaper to operate in terms of power costs." When a machine part becomes worn or damaged it can be replaced with a new part restoring the machine to its full capabilities. When a worker becomes excessively fatigued or injured it takes medical attention and time to recuperate and then he may not be able to return to a job involving lifting.

Consequently, technically advanced countries have installed machines wherever possible and relegated most workers to tasks involving occasional lifting.

Lifting Injuries

It would seem that reducing the amount of lifting would reduce the number of industrial injuries due to lifting. However, Brown (1971) stated that for the last 30 years the percentage of back injuries due to lifting has been approximately constant. He cites Department of Labour of Great Britain statistics for back injuries due to handling and lifting as 25.2 and 27.7 percent of the total industrial injuries in 1940 and 1956, respectively. Figures quoted by Troup (1965) of 25 percent for the United Kingdom and Davies (1969) of over 25 percent for England support this contention. The rate of injuries in the United States is comparable as materials handling accounts for 24 percent of "all high cost workman's compensation accidents" (Snook, Irvine, and Bass, 1970).

Since the amount of lifting has decreased and the rate of injury has remained constant, the injuries must occur during occasional lifts. Almost all workers, including office and clerical personnel, have some lifting connected with their jobs. As Anderson (1970) reports, employees doing light lifting complain of nearly as many back problems as those performing heavy manual labor.

Regulations on Lifting

Generally, attempts to reduce lifting injuries have consisted of establishing maximum acceptable weights for manual lifting. In 1967, the International Labour Conference recommended the maximum weight lifted, either regularly or occasionally, be limited to 50 kilograms (110 pounds) for adult male workers and that the maximum lifting loads required of women be substantially less. Woodsón and Conover (1970) suggest maximum weights the "average" man is able to lift, repeatedly, for objects of various sizes and shapes. Davies (1964) also cites maximum values for continuous lifting from the Great Britain Ministry of Labour of 130 pounds for men and 50 pounds for women. For repetitive lifting the American Industrial Hygiene Association (1970) has developed graphs showing the maximum object weight as a function of object width (inches away from the body) that 10, 25, 50, 75, and 90 percent of the male industrial workers should be able to lift between floor level and knuckle height, knuckle height and shoulder height, and shoulder height and arm reach. Females are restricted to 70 percent of the male values. The criteria for these values were obtained from biomechanical and psychophysical investigations of lifting tasks.

Maximum values, according to age, sex, and height were established by Poulsen and Jorgensen (1971) for lifts from floor to table height based on the standard back muscle strength. For occasional lifting, the International Occupational Safety and Health Information Centre (1962) gives maximum permissible weights for any method of lift according to age and sex. Their figures are based on the strain exerted on the lumbar discs in the spine. They stress straight-back lifting so bending forces are absorbed by the muscles.

In lieu of, or in addition to, setting maximum load limits it has been prevalent among industrial organizations to instruct employees in the use of lifting techniques which diminish the probability of an injury. Anderson (1970) has developed "kinetic handling" methods for training workers in safer manual labor techniques. Guthrie (1963) and Davies (1964) promote lifting with a straight back, chin tucked in, palmar grip, elbows into the side, knees relaxed, feet apart, and one foot in front of the other. Jones (1972) compares the mechanical, hip-flex, kinetic, dynamic, and natural methods of lifting.

Individual Lifting Capacity

While general maximum load limits and the implementation of good lifting techniques are beneficial in reducing injuries, they are not a panacea for all the complications involved in lifting. Some persons can safely lift more, and others less, than the limits permit. Also, no one lifting method is suitable for each worker in every situation. Therefore, what is needed is an accurate evaluation of each individual's lifting capacity.

Eie (1970) has developed an equation to calculate the individual lifting capacity. However, one must know the resultant axial load on the lower lumbar vertebra and anthropometrical measures such as the abdominal cross-sectional area making the equation difficult to use. Taking a somewhat different approach, Chaffin and Baker (1970) developed a computerized biomechanical model of the human body to predict an individual's capability to perform both standing and seated lifting tasks. The proficiency of the model was validated by empirical tests.

Utilization of the Force Platform

Most of the results alluded to in the previous reviews were developed from measurements of energy expenditure during lifting or the strength of the skeleto-muscular system. An alternative technique for investigating the physiological cost of lifting is to evaluate the resultant forces exerted by the body on a force platform.

Lauru (1957) was one of the forerunners in using a "detector" platform to inspect a lifting task. He compared the forces exerted by a subject going through the motions of a bent knee lifting technique to lift various weights. The conclusion was that there is no proportionality between external work produced and the internal effort produced by the muscles. Another early study involving a force platform was done by Whitney (1958). Initially, a static analysis of an isometric lifting task was performed to derive a formula predicting the vertical components of the lifting force as a function of foot placement, grasp height, and the angle of lifting formed by the arms and a vertical line through the object. Regression equations were calculated for the experimental data and the correlation coefficients were found to be highly significant. The most important variable influencing the maximum lifting force was the distance of the feet from the frontal plane of the lift. The only other variable to appreciably affect the maximum lifting force was the height of grasp.

Unfortunately, both Lauru and Whitney did not continue their research and for approximately 10 years little research was done utilizing force platforms. However, during this period several significant improvements were made which served as a foundation for an improved platform designed and built by Hearn and Konz (1968) at Kansas State University. The availability of this equipment has led to considerable research employing the force platform as a means of quantifying force exertion. Two of these scientific inquiries are particularly relevant to this inquiry.

Stueve (1968) implemented the first lifting study using the improved force platform in preparation for a paper given at the Ninth Annual Southwest Area Student Conference of American Institute of Industrial Engineers. The task consisted of six male subjects lifting and lowering a 25-pound tote box to heights of 20, 30, and 40 inches above the platform. The analysis of the data was based on energy expenditure as a function of time with units of pounds-seconds. It was found that of the two lifting techniques investigated, bending required a lower physiological cost.

While the total physiological cost is essential when assaying repetitive lifting tasks, it is a relatively unimportant criterion for evaluating occasional lifting. Instead, the maximum, or peak, forces and torques exerted are of interest as the prominent concern is to avoid a momentary overload of the skeleto-muscular system. Konz, Dey, and Bennett (1973) used the peak force as a criterion in their investigation to determine the relevance of variations in the distance of the object from the heels, the weight of the object, and the angle of turn in relation to the peak forces and torques exerted during a specified task. Depending on the criterion employed, all three parameters had a significant effect. One interesting outcome was that a reduction of object weight from 33 pounds to 11 pounds only reduced the peak force on the vertical axis by 16 percent rather than 67 percent of its prior magnitude. Upon reflection, this result is not unexpected as body weight makes up the greatest percentage of the total weight lifted by the individual.

Acceleration During Lifting

An additional parameter which has a bearing on the maximum forces and torques is acceleration of lift. The pertinence of acceleration is exemplified by Newton's law: Force = Mass x Acceleration. One of the few researchers who has published literature in this area is Zajaczkowska (1962). By attaching a set of flashing lights to the wrists of the subjects and filming the task, it was possible to compute the acceleration of lift at .1 second intervals.

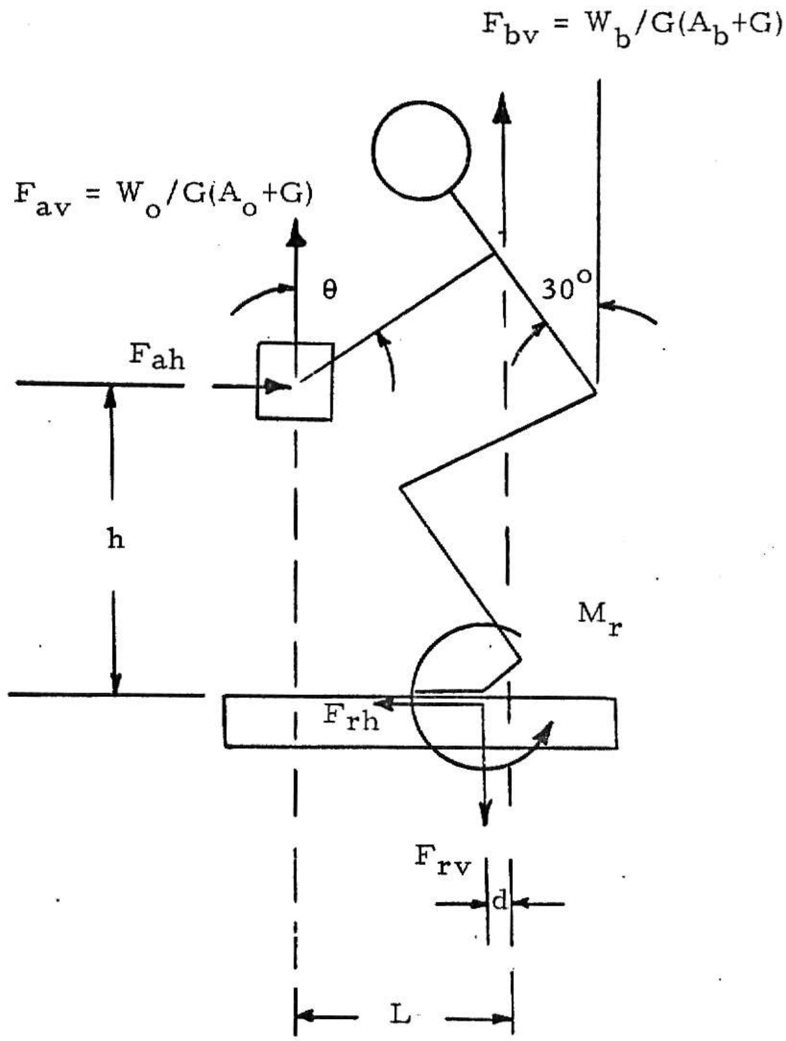
Chaffin (1968) attached a linear accelerometer to the object to directly produce a continuous curve from which the acceleration at any instant during the lift could be determined.

PROBLEM

Injuries, particularly to the lower back, due to manual lifting are of constant concern to industry. As seen by the literature review, much attention has been given to this problem. Numerous publications can be found investigating the energy expenditure in manual labor and the strength of man's skeleto-muscular system in repetitive lifting. Also, in the United States and other highly industrialized countries mechanization has eliminated most jobs requiring heavy and continuous lifting. Still the percentage of injuries due to lifting has remained constant, about 25 percent, over three decades. Obviously, many back injuries occur during occasional lifting.

The most common procedures for prevention of lifting injuries have been to teach workers proper lifting techniques and/or to set maximum acceptable weights for lifting. However, people are different. Even after extensive training few people lift exactly alike. Another approach is to measure the forces exerted by a person when lifting. As suggested by Konz (1972), the forces could be correlated to the strength of the skeleto-muscular system by use of a biomechanical model to set the individual's maximum lifting load. Consequently, the immediate problem is to measure the resultant peak forces exerted by an individual during occasional lifting. These forces are resolved into components and measured on three orthogonal axes (vertical, frontal, and lateral) by utilization of a force platform. Also, the magnitude of the torques around these axes can be determined. Advantages of the force platform are: that it is applicable to each worker, individually; the forces and torques are recorded continuously; and the measured lifting effort is independent of psychological influence. Unfortunately, most industrial organizations do not have access to a force platform. Consequently, it would be convenient to be able to predict these forces by use of formulas. The following dynamic analysis of a lifting task has been performed to ascertain the major factors affecting force exertion.

In Figure 1 the force transmitted through the arms to lift the weight has been resolved into horizontal and vertical components F_{av} and F_{ah}, respectively. Likewise, the components of the resultant force exerted through the feet on the force platform are F_{rv} in the vertical direction and F_{rh} in the horizontal direction. The other force acting on the system, F_{bv}, is the energy supplied by the back and leg muscles to lift the body. This force is shown acting through the center of gravity of the body. According to Newton's law, dynamic forces are equal to mass times acceleration. As pointed out by Zajaczhowska (1962), the total acceleration when calculating lifting forces is the sum of the acceleration of the moving object, A, and G, the acceleration of gravity which is being overcome. Moreover, it is convenient to express



Summing horizontal forces:

$$F_{rh} = F_{ah} = W_o/G(A_o+G)\tan\theta$$

Summing vertical forces:

$$F_{rv} = F_{bv}+F_{av} = W_b/G(A_b+G)+W_o/G(A_o+G)$$

Summing moments:

$$M_r = F_{av}(L-d)+F_{ah}(h)-F_{bv}(d)$$

$$= (W_o/G)(A_o+G)(L-d+h\tan\theta)-(W_b/G)(A_b+G)(d)$$

Figure 1: Dynamic Analysis of Forces During Lifting

mass in terms of weight. Therefore, the magnitude of the dynamic forces can be formulated as follows:

$$F_{bv} = (W_b/G)(A_b+G) \qquad (1)$$

$$F_{av} = (W_o/G)(A_o+G) = F_a \cos \theta; \; F_a = F_{av}/\cos \theta \qquad (2)$$

$$F_{ah} = F_a \sin \theta = (W_o/G)(A_o+G)\sin \theta/\cos \theta = (W_o/G)(A_o+G)\tan \theta \qquad (3)$$

where F_a = the force transmitted through the arms, pounds

W_o = object weight, pounds

W_b = body weight, pounds

θ = the angle formed between the arms and a vertical line through the object, degrees

Summing the forces in the horizontal direction:

$$F_{rh} = F_{ah} = (W_o/G)(A_o+G)\tan \theta \qquad (4)$$

Similarly, summing the forces in the vertical direction:

$$F_{rv} = F_{bv}+F_{av} = (W_b/G)(A_b+G) + (W_o/G)(A_o+G) \qquad (5)$$

The resultant moment of the system, M_r, acts around the lateral axis at the point the resultant force is transmitted to the platform and is equal to the sum of the moments around that point.

$$M_r = F_{av}(L-d)+F_{ah}(h)-F_{bv}(d)$$

$$= (W_o/G)(A_o+G)(L-d+h \tan \theta)-(W_b/G)(A_b+G)(d) \qquad (6)$$

where d = distance from the locus of applied force to the platform to the center of gravity of the body, inches

h = height of the center of mass of the object above the platform surface, inches

L = distance from the center of gravity of the body to center of mass of the object, inches

From the above analysis, the variables which affect force exertion are of two types. Task variables are object weight, acceleration of object, height of object above the platform, and distance from the center of gravity of the body to the center of mass of the object. Human variables are represented by body weight, location of the center of gravity of the subject's body, and the angle formed by a vertical plane through the object and the subject's arms.

While the human body is not a machine and cannot be precisely modeled with a dynamic analysis, it may be that a good approximation of the maximum forces exerted can be calculated by using the theoretical formulas. The fact that Dey (1971) recorded a force on the lateral axis is proof that the analysis is not exact. However, this force is small (about 6 pounds) and should not in itself cause an injury. The premise of this thesis is that empirical formulas determined from data taken with a force platform using least squares regression should closely approximate those calculated by dynamic analysis.

METHOD

Forces exerted during occasional lifting are affected by three principal types of variables: task variables such as weight, size, and configuration of object, and distance, rate, and rhythm of lift; technique variables including method of lift, body position, and grip; and human variables comprising age, sex, physique, and fitness. In this research it was deemed desirable to hold technique and human variables constant. Therefore, all experimentation was performed by one subject using the "squat" method of lift. Furthermore, all task variables were held as constant as possible except those which, according to dynamic analysis, directly affect force exertion.

Task

The subject stood on a six-axis force platform, lifted a 17 x 13.5 x 5 inch tote box weighted with sand, and placed it on a shelf. The box was lifted through six different heights: from 0 to 12, 24, and 36 inches above the platform; from 12 to 24 and 36 inches above the platform; and 24 to 36 inches above the platform. The edge of the shelf was 26 inches from the center of the platform. To investigate other variables affecting force exertion, the six heights were performed with a tote box weighted to 11 pounds and one weighted to 22 pounds at distances of 16 and 20 inches between the center of mass of the weighted tote box and the center of gravity of the subject. Therefore, the total number of conditions was 24 (see Table 1).

Measurement and Instrumentation

The resultant force exerted on the force platform during the lifting was measured along the vertical, frontal, and lateral axes. The torques around these axes (twist, cartwheel, and somersault for the vertical, frontal, and lateral axes, respectively) were also recorded.

The force platform was designed and built at Kansas State University by Hearn and Konz (1968). Forces on the vertical, frontal, and lateral axes are measured by linear variable differential transformers (LVDT) which detect deflections of cantilever beams under stress of the applied force. Also, there are two additional LTVD's for each axis. They are arranged so their line of action is in a plane perpendicular to one of the axes. Torques applied to the platform produce a shift in the relative position between the LTVD's. Both the beam deflections and shift in positions are transmitted as electrical impulses from the LTVD's to three Texas Instrument two-channel oscillographic recorders. A permanent output is obtained using heat-writing styli which produce a continuous trace for each of the forces and torques throughout the lift. This output may be analyzed as energy expended by determining the total area under the trace with a planimeter or by directly running the LTVD's impulses into an analog

Table 1: Experimental conditions and the sequences in which the conditions were run

Condition	Object Weight (lbs)	Distance (inches)	Height of Lift (inches)	Condition Sequence Run #1	Condition Sequence Run #2
1	11	16	0-12	21	3
2	11	16	0-24	12	16
3	11	16	0-36	10	7
4	11	16	12-24	9	17
5	11	16	12-36	22	12
6	11	16	24-36	3	22
7	22	16	0-12	18	21
8	22	16	0-24	2	19
9	22	16	0-36	1	20
10	22	16	12-24	17	13
11	22	16	12-36	24	5
12	22	16	24-36	14	18
13	11	20	0-12	13	15
14	11	20	0-24	6	9
15	11	20	0-36	15	14
16	11	20	12-24	8	24
17	11	20	12-36	19	11
18	11	20	24-36	7	1
19	22	20	0-12	4	6
20	22	20	0-24	23	8
21	22	20	0-36	5	10
22	22	20	12-24	11	23
23	22	20	12-36	16	2
24	22	20	24-36	20	4

integrating circuit. On the other hand, the maximum deviations of the trace, representing the maximum force or torque exerted during the lift, may be the desired criteria. As injuries are more likely to occur at the point of maximum force exertion, this study is concerned with the maximum deflections of the trace.

Before any data was taken, the force platform was calibrated for maximum sensitivity. With the exception of the vertical force the method of calibration consisted of setting a base line for the force or torque with no weight on the platform and adjusting the corresponding LVTD's to obtain the maximum deviations of the trace for applications of ten pounds force or 120 inch-pounds torque. The number of millimeters the traces deviated from the base lines were then used to calculate conversion factors to transform the recorder output into pounds and inch-pounds. Calibration of the vertical axis differed only in that the base line was set while the subject was standing on the platform. The purpose of this procedure was to avoid a loss of sensitivity due to the added weight of the subject after the scale was calibrated with no weight on it.

In addition, the acceleration of the object during the lift was recorded on a Beckman Type RS Dynagraph recorder using a Beckman 9803 strain gage coupler and an Entran linear accelerometer. The accelerometer, fundamentally a strain gage apparatus, operated as a system of four gage-elements arranged in a Wheatstone bridge circuit.

When a small mass located in the accelerometer is strained by the force of acceleration, the resistance of each individual element undergoes a slight change. The function of the 9803 coupler is to adapt the output of the accelerometer for amplification and recording. Also, in order to prevent an excessive shock to the accelerometer which might distort its trace, each shelf was padded with terry cloth. Calibration was accomplished by rotating the accelerometer 180 degrees which caused the recorder stylus to deviate from the base line a distance proportional to two G (acceleration of gravity). The number of millimeters encompassed by the deviation was subsequently used to calculate a conversion factor to transform the output into units of feet per second squared.

All calibrations were checked before each run and at the completion of the experiment.

Subjects

As mentioned previously, this research was limited to one subject to hold the human variables constant. The subject was an adult male 23 years of age, 68.5 inches tall, weighing 145 pounds, having excellent health, and in good physical condition. The subject was paid for his participation in the experiment. He has been a subject in two previous lifting experiments and was familiar with the lifting techniques used in the task. However, to assure smooth and steady lifts throughout the experiment, the subject was given extensive pretest training. The training consisted of ten minutes' practice with the experimenter watching, a replay of this session on videotape including comments by the experimenter, and an additional ten-minute practice session.

Procedure

Using a random number table, two sequences were obtained for performing the 24 conditions encompassed by the task. To counterbalance any serial effects, the sequences were also performed in reverse. A run consisted of a complete sequence of the 24 conditions. Thus, there were four runs.

Before each run the center of gravity of the subject was placed over the center of the force platform. This was accomplished by having the subject adjust his position on the platform until the cartwheel and somersault torques registered zero. The placement of the subject's feet was delineated with tape so his position would not shift appreciably throughout the complete set of trials. Next, the subject was given 20 "warm-up" lifts under the inspection of the experimenter. After the preparatory session, three lifts were made for each condition, one every 20 seconds with a one-minute interval between conditions. Therefore, each run encompassed 72 lifts in a 45-minute period. Including all four runs, there were 12 lifts per condition and a total of

288 lifts in the experiment. Between lifts the experimenter took the tote box from the shelf and placed it in the initial lifting position.

Figure 2: Subject Performing a Lift for Condition 6

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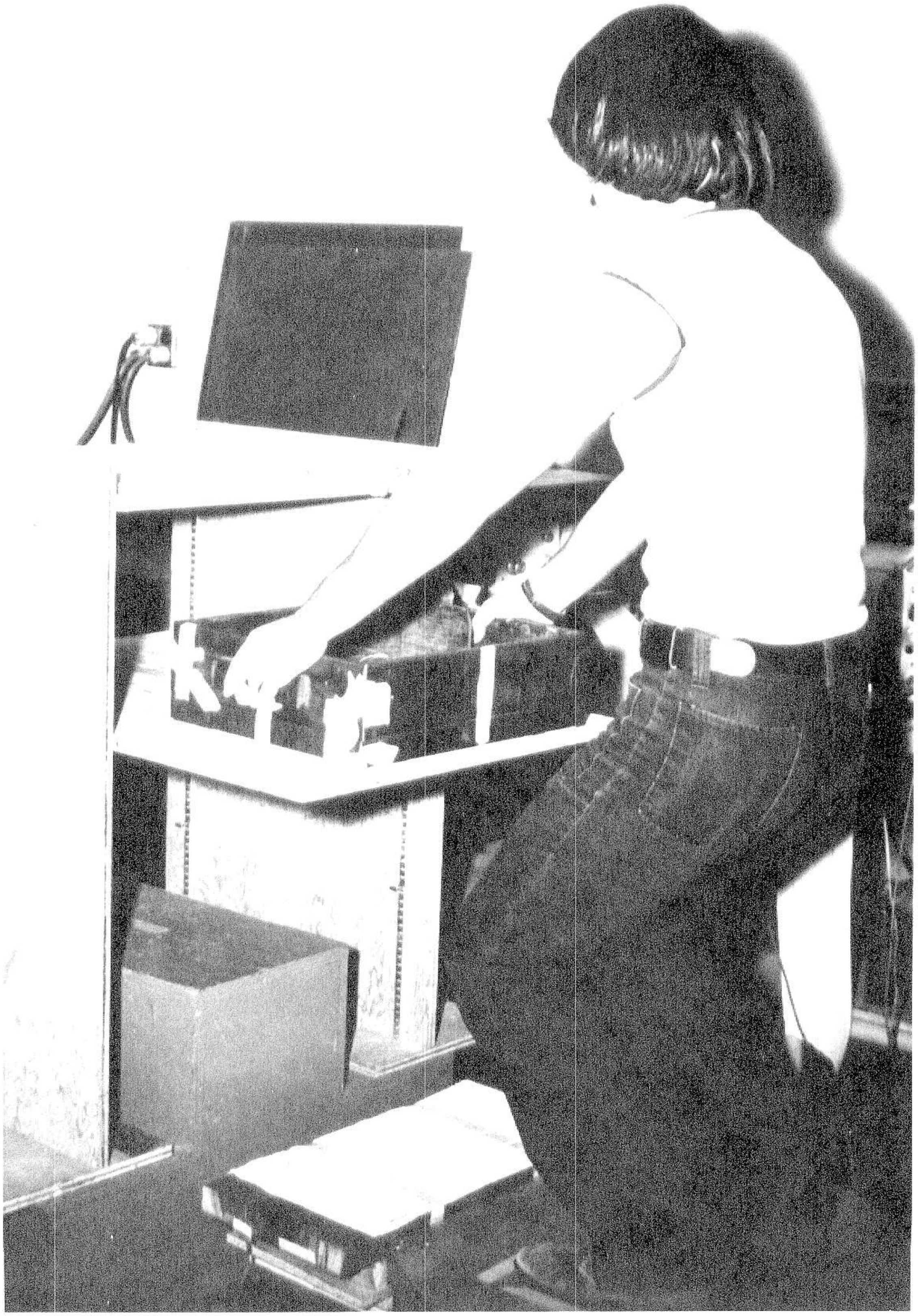

RESULTS AND DISCUSSION

The maximum forces and torques produced were consistent over the twelve trials for each condition. This is shown by the small coefficients of variation in Table 2.

Elapsed Time During a Lift

The average elapsed time during a lift varied from 3.5 seconds through a height of 24 to 36 inches above the platform surface to 5.0 seconds through a height of 0 to 12 inches above the platform surface. By inspection of Table 3, it is evident that the lifting time was not altered by changing the object weight or the distance from the center of mass of the object to the center of gravity of the man, but varied only according to the height of lift. These values were determined from the chart speed, 5 mm/sec, of the oscillograph recorders and substantiated by timing a videotape playback of the tasks with a stop watch.

Analysis of Recorder Output

Typical outputs from the oscillograph recorders are shown in Figures 3, 4, and 5 for the vertical force, frontal force, and somersault torque. When the subject is standing motionless on the platform the trace for each force and torque consists of a straight horizontal line. Forces and torques produced in the performance of a lifting task were recorded as defections to either side of the line. Deflections below this line indicate that the resultant forces on the platform are

Table 2: Coefficients of Variation ($\sigma/\bar{x}$)

Condition	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	0.3	0.2	0.1	0.2	0.5	0.2	0.4
2	0.3	0.4	0.3	0.1	0.2	0.1	0.1
3	0.4	0.4	0.2	0.1	0.3	0.2	0.1
4	0.4	0.4	0.1	0.1	0.2	0.3	0.2
5	0.3	0.2	0.2	0.1	0.5	0.2	0.1
6	0.4	0.2	0.1	0.1	0.3	0.3	0.1
7	0.3	0.3	0.1	0.1	0.4	0.3	0.2
8	0.3	0.4	0.1	0.1	0.3	0.2	0.1
9	0.3	0.2	0.2	0.1	0.2	0.2	0.2
10	0.3	0.2	0.2	0.1	0.2	0.3	0.1
11	0.4	0.2	0.2	0.1	0.3	0.2	0.2
12	0.3	0.2	0.2	0.0	0.4	0.2	0.0

Table 2 (continued)

Condition	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
13	0.3	0.2	0.2	0.1	0.4	0.2	0.3
14	0.3	0.2	0.1	0.1	0.3	0.3	0.2
15	0.3	0.2	0.1	0.1	0.2	0.3	0.2
16	0.3	0.2	0.3	0.1	0.3	0.3	0.2
17	0.3	0.2	0.2	0.1	0.3	0.2	0.2
18	0.3	0.3	0.6	0.1	0.4	0.3	0.2
19	0.4	0.4	0.2	0.1	0.4	0.0	0.2
20	0.3	0.2	0.0	0.1	0.3	0.3	0.2
21	0.3	0.2	0.2	0.1	0.3	0.2	0.2
22	0.3	0.3	0.3	0.1	0.4	0.4	0.1
23	0.3	0.3	0.3	0.1	0.2	0.2	0.1
24	0.3	0.3	0.5	0.1	0.3	0.3	0.4

Table 3: Mean time (seconds) to complete a lift

Object Weight (lbs)	11	22	11	22	
Distance, L (in)	16	16	20	20	
Height of Lift (in)	**Time**				**Mean**
0-12	5.0	5.0	4.5	5.0	4.9
0-24	4.8	4.8	4.5	4.8	4.7
0-36	4.5	4.5	4.5	4.5	4.5
12-24	4.0	4.0	4.0	4.0	4.0
12-36	4.5	4.5	4.0	4.5	4.4
24-36	3.5	3.5	3.5	3.5	3.5
Mean	4.4	4.4	4.2	4.4	4.3

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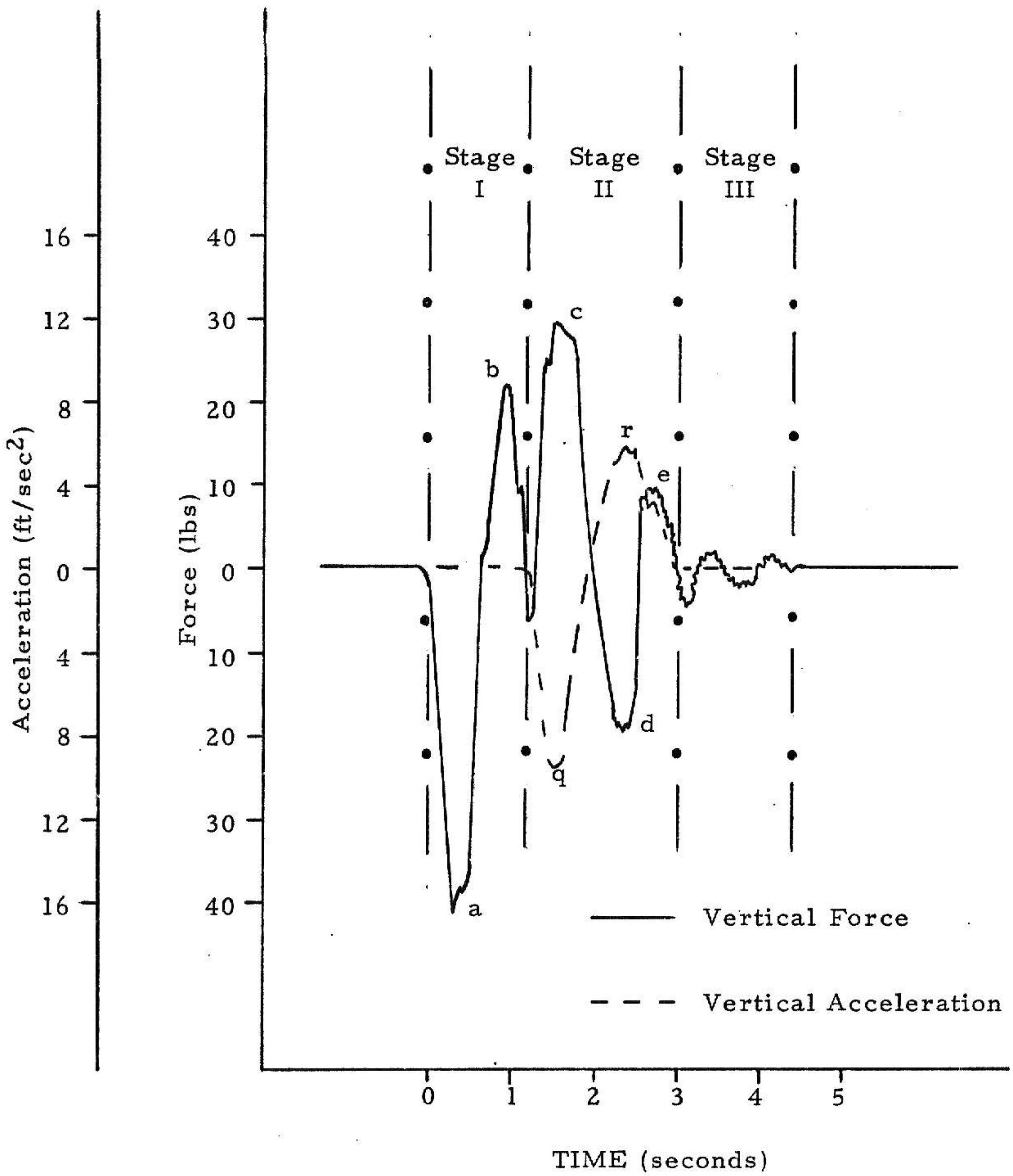

Figure 3: Vertical Force and Acceleration Versus Time

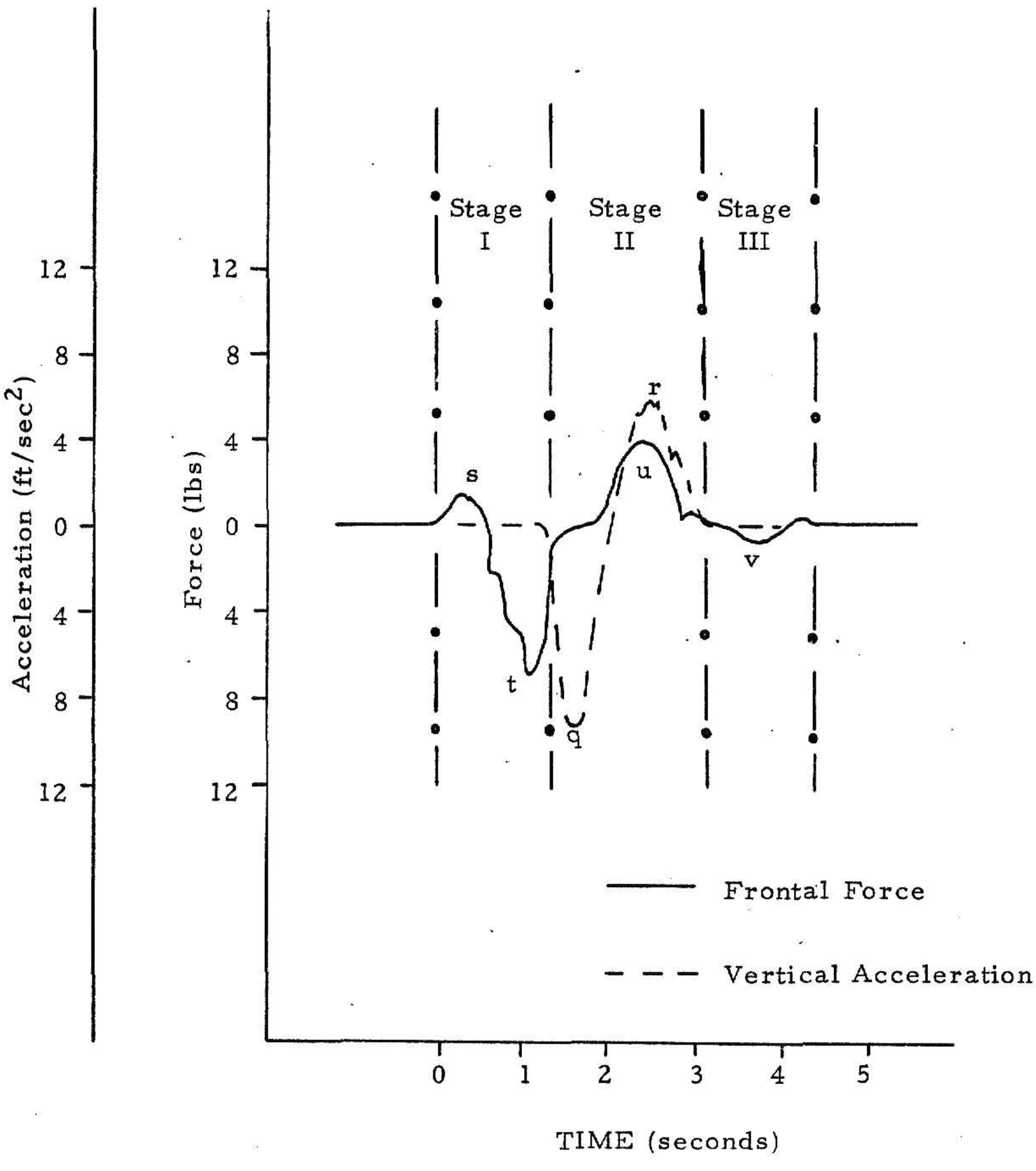

Figure 4: Frontal Force and Acceleration Versus Time

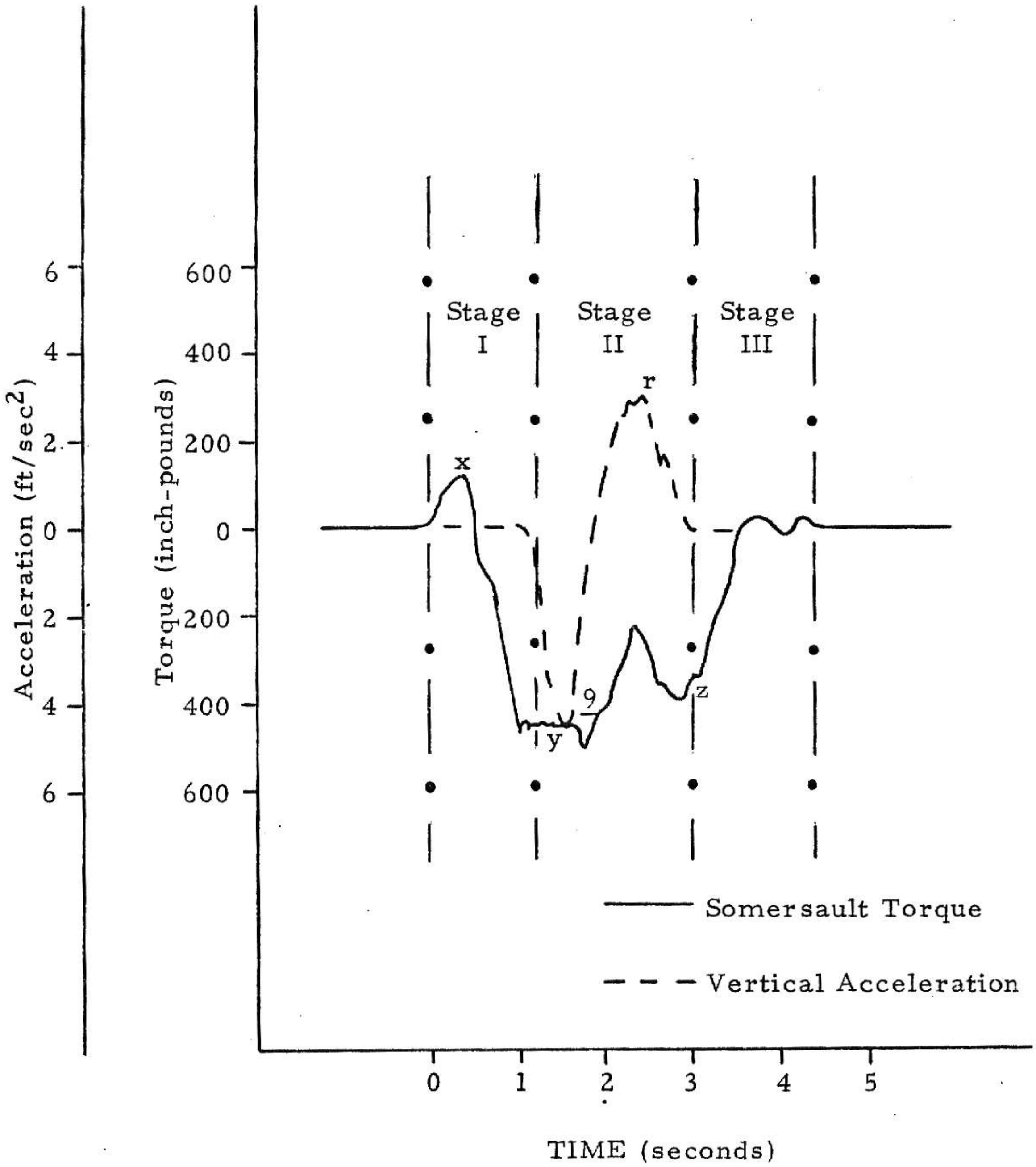

Figure 5: Somersault Torque and Acceleration Versus Time

upward, forward, and to the left for the vertical, frontal, and lateral axes, respectively. Conversely, deflections above the horizontal line indicate the resultant forces on the platform surface are downward, backward, and to the right for the vertical, frôntal, and lateral axes, respectively. Similarly, torques exerted in the directions as shown in Figure 6 produce deflections below the horizontal base line while torques in the opposite directions produce deviations above the horizontal base line. Consequently, a permanent record is obtained of both the magnitude and direction of the forces and torques exerted during a lifting task.

As verification of the premise of this paper is contingent upon a relationship between acceleration and force, a vertical acceleration curve was plotted against the typical output for the forces on the vertical and frontal axes and also the torque around the lateral axis (somersault). No typical output was graphed for lateral force or cartwheel and twist torque because no basic pattern emerged in the data; the magnitude of the maximum peaks for these three occurred haphazardly in time and direction.

Analysis of vertical force. Referring to Figure 3, the initial 1.2 seconds of the task is expended by the subject in assuming a squat position prior to the actual lift. Hence, this portion of the task is called Stage I. Peak (a) denotes an upward vertical force as the body starts its motion. Therefore, at this point in time the force exerted on the platform surface is less than the force due to body weight when the

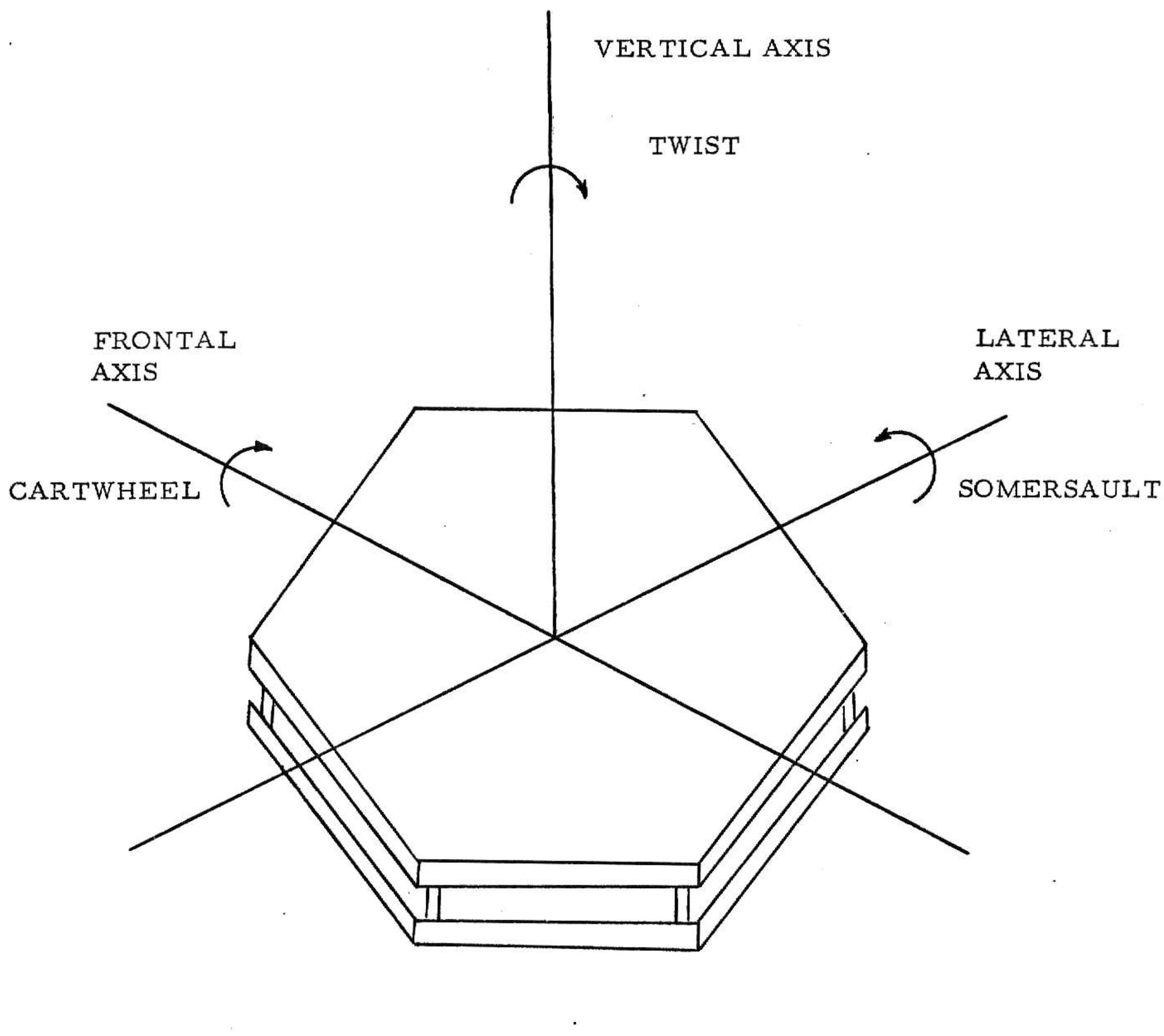

Figure 6: Cartwheel, Twist, and Somersault Torques

subject is stationary. Peak (b) represents the force exerted downward as the body approaches the squat position. The next 1.8 seconds of the task, Stage II, was required to lift the object and place it on the shelf. During this period a curve for the acceleration of the object was obtained from the Beckman recorder. Peak (c), acting downward in reaction to the effort exerted to lift the object and the body, coincides with the peak acceleration of the object, Peak (q). Peak (d), acting upwardly due to the force arresting the inertia of the object preparatory to placing it on the shelf, is accompanied by a deceleration of the object, Peak (r). As the lift progresses with a smooth and steady motion, the object continues to decelerate until it comes to rest on the shelf. However, since during this motion the object must be raised slightly above the shelf, the effort required to place it there produces a downward force. Consuming the final 1.4 seconds of the task is Stage III. During this time the subject returns to the original upright position creating only minimal forces on the vertical axis.

Out of 288 trials, 52% of the maximum forces on the vertical axis occurred on Peak (a), 34% on Peak (c), and 14% occurred simultaneously on Peak (a) and Peak (c). Although the acceleration of the body was not measured, a comparison of the time taken for each stage of the task reveals that the subject moved at a higher rate of speed when assuming the squat position prior to the lift than during any other portion of the task. The weights of the objects used in this study were light in relation to established maximum load limits. Consequently, for a majority of the trials the effect of increased total weight, object plus body weight, did not equal the effect of the increased acceleration of the body while assuming the squat position.

The import of this phenomenon is that it discloses a potential danger point, Peak (a), at which an injury could occur during occasional lifting.

Analysis of frontal force. Stage I of the frontal force commences with a slight backwards force, Peak (s), as motion is initiated and then switches to the forward direction and increases in magnitude, Peak (t). In Stage II, no distinguishable force is observed during the acceleration of the object, Peak (q). However, deceleration of the object, Peak (r), is accompanied by a force in the backward direction, Peak (u). After the object is released and Stage III begins, a forward force, Peak (v), is generated as the subject returns to the original upright position.

The most interesting aspect of the trace for the frontal force is the absence of any correlation between force and acceleration. This violates the theoretical formula for frontal force and denotes the influence of an unknown variable.

On 75% of the 288 trials the maximum frontal force occurred on Peak (t). This coincides in time with the most prevalent peak of maximum vertical force, Peak (a), and implies a relationship between the two. Again, as with vertical force, the peak frontal force occurs as the subject approaches the squat position, before the load is ever lifted.

Analysis of somersault torque. Throughout the task, with the exception of a slight initial deviation, Peak (x), any appreciable deflection of the trace is entirely below the horizontal base line. The maximum torque, Peak (y), is reached before the lift begins and continues throughout the acceleration of the object, decreases during deceleration of the object, and subsequently rises to a lesser peak as the object is placed on the shelf. This suggests that the center of gravity of the body is shifted forward during the task. Furthermore, for the weights investigated, the resultant torque is dependent on body weight to a greater extent than on object weight.

Effect of Distance, L, on Forces and Torques

As seen by the theoretical dynamic analysis, an increase in L, the distance from the center of mass of the object to the center of gravity of the body should increase the frontal force and the somersault torque. Referring to Figure 1, when L increases there is a corresponding increase in the angle formed by the arms and a vertical plane through the center of mass of the object, θ. Upon examination of Equation (4) it is noted that by increasing L, the value of tan θ is increased resulting in a frontal force of greater magnitude. Accordingly, from Equation (b), L directly, and indirectly through tan θ, influences the somersault torque.

Equation (5) does not contain any variables affected by L; thus, the vertical force is not influenced. Since cartwheel torque, twist torque, and lateral force do not theoretically exist, variations in L should not affect their values.

To test the above suppositions a two-tailed t-test was performed on paired comparisons for each force and torque. Using the mean experimental values, conditions were paired such that L and θ were the only attributes which did not match. Object weight and height of lift were identical within each set of paired conditions. For example, condition 1 was paired with condition 13. At an $\alpha = .05$ level the peak force exerted on the frontal axis and the peak somersault torque was significantly greater for lifting an object whose center of mass was placed at 20 inches rather than 16 inches from the center of gravity of the body. No significant difference was discerned for vertical force, lateral force, cartwheel torque, and twist torque. Therefore, the results of the above statistical tests provide some support to the theoretical analysis in that L had a meaningful influence on the experimental outcome only for the quantities in which it was a theoretically designated variable.

In addition, a paired comparison t-test showed no significant difference in acceleration of the object was incurred by varying L. Likewise, no theoretical relationship for acceleration was developed between the two distances.

Effect of Object Weight, W, on Forces and Torques

Equations (1), (2), and (3) all include object weight as a dependent variable. According to these formulas there should be a difference between the experimental results achieved for lifting the 11-pound object and the values obtained when lifting the 22-pound object for the vertical force, frontal force, and somersault torque. Such a divergence was validated by submitting the experimental data to paired comparison t-tests at an $\alpha = .05$ level. The forces on the vertical and frontal axes and the torque around the lateral axis (somersault) were found to be significantly greater when lifting an object weighing 22 pounds versus lifting one weighing 11 pounds. While there was no significant difference between the two weights for the lateral force and cartwheel torque, twist torque was significantly greater for the 22-pound object. Thus, twist torque violates the theoretical hypothesis as it is dependent on object weight.

Also, an increase in object weight from 11 to 22 pounds corresponded to a significant decrease in acceleration of the object. Such a trend is desirable because the two parameters work towards counteracting each other and thereby reduce the maximum forces and torques.

Effect of Height of Lift, h, on Forces and Torques

In order to determine if the peak forces and torques were affected by the height through which the object was lifted, paired comparison

Table 4: Results of paired comparison tests

	11 Versus 22 lb Weight	16 Versus 20 inch Distance
Vertical Force	22 lb sign. greater	no sign. difference
Frontal Force	22 lb sign. greater	20 inch sign. greater
Lateral Force	no sign. difference	no sign. difference
Somersault Torque	22 lb sign. greater	20 inch sign. greater
Cartwheel Torque	no sign. difference	no sign. difference
Twist Torque	22 lb sign. greater	no sign. difference
Acceleration of Object	11 lb sign. greater	no sign. difference

t-tests were executed between the six different heights. The mean experimental values for each condition were used in the calculations.

The sole quantity which noticeably varied with the height of lift was vertical force. With exception of the 0-24 and 0-36 inch lifts, the peak vertical forces were significantly different for all of the heights lifted. The 0-12 inch lift produced significantly greater forces than any of the other heights for the frontal axis. Otherwise, the frontal force did not vary significantly with the height of lift. Along the lateral axis the 24-36 inch lifts resulted in significantly smaller forces than those produced when lifting through any of the other heights. All other variations in the lateral force due to height of lift were insignificant.

While the deviation between somersault torques occurring at heights of 12-24 inches and 24-36 inches was insignificant, these forces were significantly lower than those corresponding to any of the other four heights. All variations in cartwheel torque, twist torque, and acceleration of the object due to altering the height of lift were insignificant.

Theoretical Values Versus Empirical Results

According to the dynamic analysis, F_{rv}, F_{rh}, and M_r should predict the experimental values, as measured by the force platform, for vertical force, frontal force, and somersault torque, respectively. However, the variables θ, A_b, and d were not quantified during the performance of the task and must be estimated before Equations (4), (5), and (6) can be used to calculate the theoretical values.

Since the body travels through less distance than the object during the lift, the acceleration of the body, A_b, has a value between zero and the acceleration of the object. The mean peak acceleration of the object for all conditions was 9.33 ft. per sec.^{2}. Thus, the peak acceleration of the body was estimated to be 5.0 ft. per sec.^{2} for all conditions. Because the acceleration of the body acts complementary to the acceleration of gravity and its relative value is small, the maximum error introduced due to the estimation should be less than 10%.

To determine d, the distance from the center of gravity of the body to the locus of applied force to the platform surface, and θ, the angle subtended by the arms and a vertical plane through the center of mass of the object, it is necessary to know the point in time during the lift at which the maximum stresses occur. According to Troup (1965): "In lifting, the greatest stresses arise at the beginning, when the inertia of the weight has to be overcome and the load accelerated." Also, the traces for the vertical force and somersault torque show the peak values to occur near the beginning of the lift. Therefore, values of θ used in the theoretical calculations were obtained by measuring the angle formed with the subject in the squat position, grasping the tote box to simulate the beginning of the lift. The angle varied only with the distance L, subtending 29 degrees at 16 inches and 35 degrees at 20 inches. The accuracy of the measurements were tested by the following proportion:

$$\theta/L = 29/16 = 35/20$$

To obtain the values of d, the subject was asked to simulate his position at the beginning of the lift. While holding this posture the subject's position was adjusted until the somersault and cartwheel torques registered zero torque. The above torques are zero when the center of gravity of the body is over the center of the platform. Subsequently, d could be directly measured. These values varied with the distance, L, and the initial height of lift (Table 5).

While the height through which the object was lifted was a controlled variable for the task, the position of the object changes with time during the lift. For the purpose of calculating theoretical values of F_{rv}, F_{rh}, and M_r, the value of h was taken to be the height of the object one-quarter of the way through the lift.

When comparing the resulting theoretical values for vertical force, frontal force, and somersault torque in Table 7 with the experimental means in Table 6 large discrepancies are observed. To determine if these discrepancies are due to a constant factor, a stepwise multiple regression program was used to establish a linear relationship between the theoretical and the mean experimental values in Tables 6 and 7. In the following relationships the theoretical values are the dependent variables and the maximum experimental values are the independent variables.

$$\text{theoretical vertical force (lbs)} = -17.38 + .31 \text{ (experimental mean, lbs)} \qquad (7)$$

standard error = 7.87 lbs

Table 5: Distance, d, from the locus of applied force to the platform to the center of gravity of the body, inches

	Height Above Platform (in)			
	0	12	24	36
16 inches	1.0	1.5	2.0	2.5
20 inches	0.5	1.0	1.5	2.5

Table 6: Maximum experimental mean values of forces (lbs), torques (in-lbs), and acceleration (ft/sec^2) for each condition

Condition	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	42.5	7.2	2.6	394.4	72.5	62.5	11.1
2	45.6	5.8	2.7	432.2	81.3	62.5	10.6
3	47.2	4.9	3.2	420.0	70.0	60.0	12.8
4	32.8	4.3	1.9	354.4	78.8	50.0	9.3
5	37.2	5.4	2.2	392.2	82.5	55.0	11.3
6	28.3	5.8	1.8	368.9	57.5	45.0	8.5
7	45.3	8.2	3.1	425.6	95.0	55.0	8.7
8	51.9	7.0	2.9	468.9	82.5	72.5	10.7
9	51.7	6.8	2.6	465.6	73.8	82.5	9.7
10	35.6	5.2	2.1	392.2	72.5	57.5	8.1
11	38.6	5.8	2.1	420.0	70.0	55.0	9.2
12	31.4	5.5	1.6	385.6	70.0	57.5	6.2

Table 6 (continued)

Condition	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
13	42.8	8.0	2.7	417.8	77.5	55.0	8.3
14	45.6	5.8	2.7	425.6	72.5	52.5	12.1
15	46.7	6.1	2.9	417.8	88.8	55.0	9.7
16	33.6	5.0	1.8	371.1	67.5	50.0	9.7
17	39.4	6.0	2.1	405.6	65.0	57.5	9.5
18	22.2	5.5	1.4	381.1	55.0	52.5	8.5
19	45.6	8.0	3.1	427.8	86.3	60.0	5.5
20	48.6	7.3	2.7	445.6	82.5	67.5	9.2
21	50.3	7.2	3.0	506.7	75.0	70.0	10.0
22	34.4	5.4	2.7	424.4	85.0	60.0	7.8
23	39.2	7.0	2.3	461.1	78.8	55.0	8.1
24	30.3	6.5	1.6	414.4	76.3	57.5	9.2
Mean	40.3	6.2	2.4	417.4	75.7	58.6	9.3

Table 7: Theoretical maximum values of forces (lbs) and torques (in-lbs)

Condition	Vertical Force	Frontal Force	Somersault Torque
1	182.3	8.2	78.8
2	182.2	8.1	116.9
3	182.9	8.5	165.4
4	181.7	7.9	72.5
5	182.4	8.2	128.5
6	181.4	7.7	167.5
7	195.4	15.4	297.6
8	196.8	16.3	402.6
9	196.1	15.9	452.2
10	195.1	15.3	377.5
11	195.8	15.7	472.0
12	193.8	14.6	425.6
13	181.4	9.7	215.2
14	182.7	10.6	296.3
15	181.8	10.0	315.6
16	181.8	10.0	254.7
17	181.8	10.0	302.9
18	181.4	9.7	268.6
19	193.3	18.1	473.2
20	195.8	19.8	625.8
21	196.4	20.2	721.5
22	194.8	19.1	638.6
23	195.1	19.3	742.1
24	195.8	19.8	806.1
Mean	188.7	13.3	363.2

theoretical frontal force (lbs) = 4.77 + .11 (experimental mean, lbs) (8)

standard error = 0.98 lbs

theoretical somersault torque (in-lbs) = 380.13 + .10 (experimental mean, in-lbs) (9)

standard error = 28.53 in-lbs

The above relationships show equations (4), (5), and (6) provide some indication of the forces and torques exerted during light lifting and that the values of some of the variables used to calculate the theoretical were incorrect.

In an attempt to identify which variables are the major sources of error in calculating the theoretical values, the empirical results and theoretical variables were equated and entered into a multiple regression equation. If the predictive power of equations (4), (5), and (6) had been exact, the coefficients of the independent variables in the following expressions would have been unity and the y-intercept would have been zero.

$$\text{actual vertical force, lbs} = 153.65 + 0.23(F_{av}, \text{lbs}) - 0.70(F_{bv}, \text{lbs}) \quad (10)$$

standard error = 7.34 lbs

$$\text{actual frontal force} = 4.87 + 0.10(F_{ah}, \text{lbs}) \quad (11)$$

standard error = 1.16 lbs

$$\text{actual somersault torque} = 400.28 + .15(F_{av}, \text{lbs})(L\text{-}d, \text{in}) + 0.00(F_{ah}, \text{lbs})(H, \text{in}) - .21(F_{bv}, \text{lbs}) \times (d, \text{in}) \quad (12)$$

standard error = 22.85 in-lbs

According to the above relationships, the force required to lift the body's weight, F_{bv}, is the theoretical variable which most influences the actual vertical force and somersault torque. Since in equation (10) F_{bv} is negative in sign and it is positive in sign in the corresponding theoretical formula, equation (5), the effect of the body during lifting seems to be a major source of error in the predictive power of the dynamic analysis. As the body is a complicated machine it will probably require a complex dynamic analysis in which the body is divided into segments to accurately quantify its effect on the resulting forces and torques during a lifting task.

CONCLUSIONS

The maximum peaks for vertical and frontal force occur before the load is lifted. Therefore, this is a potential danger point at which an injury could occur during squat lifting with light loads. By exercising caution in this portion of the lift the danger will be lessened.

The results of the paired comparison t-tests signify that the variables L, the distance from the center of gravity of the body to the center of mass of the object, and W_o, the weight of the object, influence the empirical results as designated by the theoretical formulas. Also, the peak vertical forces corresponded with the peak accelerations. Hence, the dynamic analysis was useful in identifying some of the variables affecting the maximum forces and torques.

However, while formulas (4), (5), and (6) gave an indication of the maximum forces and torques produced during the task, their capabilities to predict the actual forces and torques exerted during the task was poor. It is felt the analysis of a more complex model would yield better results. The hypothesis that body weight is the biggest factor affecting the maximum forces and torques is supported by the evidence that the peak vertical and frontal forces occurred before the object was lifted. Also, throughout the task the somersault torque was always applied forward around the lateral axis. This suggests the center of gravity of the body was shifted forward during the performance of the task. Consequently, an approach to further research in this area would be to divide the body into separate segments before executing the dynamic analysis.

Table 8: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration ($ft\text{-}sec^2$) for condition 1

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	60.0	6.0	2.3	466.7	105.0	60.0	8.3
2	53.3	5.0	2.7	480.0	90.0	90.0	8.3
3	46.7	5.0	2.3	533.3	60.0	90.0	8.3
4	43.3	8.0	2.3	386.7	30.0	60.0	10.4
5	43.3	9.0	3.7	386.7	30.0	60.0	12.5
6	43.3	8.0	2.7	400.0	60.0	60.0	18.7
7	20.0	6.0	2.7	346.7	60.0	60.0	
8	20.0	6.0	2.7	373.3	75.0	60.0	
9	23.3	8.0	3.3	320.0	180.0	60.0	
10	56.7	9.0	2.0	360.0	60.0	60.0	
11	46.7	10.0	2.0	360.0	60.0	60.0	
12	53.3	6.0	3.0	320.0	60.0	30.0	

Table 9: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 2

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	50.0	4.0	2.0	386.7	75.0	60.0	11.4
2	50.0	5.0	3.7	413.3	90.0	60.0	11.4
3	46.7	3.0	2.3	506.7	60.0	60.0	11.4
4	36.7	5.0	3.0	426.7	60.0	90.0	8.3
5	66.7	7.0	2.0	386.7	75.0	60.0	10.6
6	46.7	4.0	2.7	413.3	90.0	60.0	10.6
7	26.7	5.0	2.0	440.0	120.0	60.0	
8	26.7	5.0	3.3	440.0	90.0	60.0	
9	26.7	5.0	2.0	453.3	75.0	60.0	
10	53.3	9.0	4.7	466.7	105.0	60.0	
11	60.0	10.0	2.3	453.3	75.0	60.0	
12	56.7	7.0	2.0	400.0	60.0	60.0	

Table 10: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 3

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	46.7	2.0	3.0	373.3	60.0	60.0	11.4
2	43.3	2.0	3.3	453.3	75.0	60.0	10.4
3	60.0	3.0	3.7	453.3	30.0	90.0	13.5
4	46.7	8.0	3.3	453.3	60.0	30.0	12.5
5	53.3	4.0	2.7	400.0	90.0	60.0	14.5
6	66.7	8.0	5.3	400.0	90.0	60.0	14.5
7	20.0	5.0	2.3	400.0	45.0	60.0	
8	26.7	5.0	1.7	426.7	60.0	60.0	
9	20.0	6.0	3.7	400.0	90.0	60.0	
10	66.7	6.0	3.0	440.0	75.0	60.0	
11	40.0	6.0	3.3	413.3	105.0	60.0	
12	76.7	4.0	3.3	426.7	60.0	60.0	

Table 11: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 4

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	40.0	3.0	2.0	373.3	75.0	30.0	11.4
2	33.3	3.0	1.7	386.7	60.0	30.0	9.3
3	36.7	2.0	1.7	373.3	60.0	30.0	8.3
4	30.0	5.0	2.3	426.7	90.0	60.0	10.4
5	30.0	5.0	2.0	360.0	75.0	60.0	6.2
6	30.0	4.0	1.0	373.3	60.0	60.0	10.4
7	13.3	4.0	1.7	373.3	90.0	60.0	
8	13.3	3.0	3.0	293.3	90.0	60.0	
9	20.0	3.0	2.0	293.3	75.0	60.0	
10	40.0	8.0	2.0	346.7	120.0	60.0	
11	46.7	8.0	1.3	333.3	60.0	30.0	
12	60.0	4.0	2.0	320.0	90.0	60.0	

Table 12: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 5

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	53.3	4.0	3.7	400.0	180.0	30.0	12.5
2	40.0	4.0	1.3	400.0	60.0	30.0	10.4
3	40.0	5.0	2.0	413.3	60.0	60.0	10.4
4	40.0	7.0	2.3	346.7	45.0	60.0	12.5
5	43.3	7.0	2.7	413.3	90.0	60.0	12.5
6	40.0	5.0	2.3	373.3	90.0	60.0	9.3
7	16.7	6.0	1.3	320.0	60.0	60.0	
8	20.0	5.0	2.0	346.7	90.0	60.0	
9	23.3	4.0	1.0	306.7	30.0	60.0	
10	46.7	7.0	2.0	440.0	135.0	60.0	
11	43.3	6.0	2.7	493.3	75.0	60.0	
12	40.0	5.0	2.7	453.3	75.0	60.0	

Table 13: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 6

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	30.0	5.0	2.7	386.7	30.0	60.0	9.3
2	26.7	4.0	1.7	373.3	60.0	60.0	8.3
3	33.3	4.0	1.7	360.0	30.0	60.0	7.3
4	26.7	5.0	1.3	346.7	60.0	30.0	9.3
5	20.0	5.0	1.0	333.3	45.0	30.0	8.3
6	23.3	6.0	2.0	373.3	60.0	30.0	8.3
7	16.7	8.0	2.0	373.3	105.0	60.0	
8	13.3	6.0	1.7	373.3	75.0	60.0	
9	13.3	6.0	1.0	373.3	45.0	60.0	
10	50.0	7.0	2.7	440.0	60.0	30.0	
11	43.3	8.0	2.0	373.3	60.0	30.0	
12	43.3	6.0	2.3	320.0	60.0	30.0	

Table 14: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 7

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	60.0	6.0	2.7	440.0	90.0	60.0	11.4
2	53.3	6.0	2.7	426.7	60.0	60.0	10.4
3	46.7	10.0	2.7	413.3	60.0	60.0	9.3
4	50.0	6.0	3.0	453.3	135.0	30.0	6.2
5	53.3	8.0	4.0	426.7	90.0	30.0	6.2
6	60.0	6.0	3.7	506.7	150.0	30.0	8.3
7	20.0	8.0	2.7	453.3	105.0	60.0	
8	16.7	7.0	3.7	400.0	180.0	60.0	
9	23.3	6.0	2.7	400.0	60.0	60.0	
10	56.6	14.0	3.0	373.3	75.0	90.0	
11	50.0	12.0	2.7	426.7	60.0	60.0	
12	53.3	9.0	3.3	386.7	75.0	60.0	

Table 15: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 8

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	50.0	6.0	2.7	413.3	120.0	60.0	8.3
2	53.3	4.0	2.7	453.3	120.0	60.0	10.4
3	50.0	4.0	3.3	506.7	60.0	60.0	10.4
4	53.3	8.0	3.0	453.3	75.0	90.0	10.4
5	63.3	9.0	2.7	520.0	75.0	60.0	12.5
6	70.0	4.0	4.0	493.3	60.0	90.0	12.5
7	30.0	6.0	2.7	466.7	75.0	90.0	
8	30.0	5.0	2.3	453.3	60.0	90.0	
9	33.3	5.0	3.0	493.3	75.0	90.0	
10	70.0	12.0	2.7	466.7	75.0	60.0	
11	53.3	10.0	3.3	453.3	105.0	60.0	
12	66.7	11.0	2.3	453.3	90.0	60.0	

Table 16: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration ($ft\text{-}sec^2$) for condition 9

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	53.3	5.0	3.3	466.7	90.0	90.0	10.4
2	53.3	6.0	2.7	520.0	60.0	90.0	9.3
3	53.3	6.0	2.0	466.7	90.0	90.0	9.3
4	56.7	8.0	3.3	480.0	75.0	90.0	6.2
5	70.0	10.0	2.7	480.0	60.0	90.0	12.5
6	53.3	8.0	3.7	480.0	60.0	90.0	10.3
7	26.7	4.0	2.0	453.3	90.0	90.0	
8	30.0	6.0	2.3	426.7	60.0	90.0	
9	30.0	6.0	2.0	426.7	60.0	90.0	
10	50.0	7.0	2.3	453.3	60.0	60.0	
11	70.0	8.0	2.0	480.0	75.0	60.0	
12	73.3	7.0	3.0	453.3	105.0	60.0	

Table 17: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 10

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	43.3	4.0	2.3	413.3	90.0	60.0	7.3
2	33.3	5.0	1.0	440.0	60.0	60.0	8.3
3	46.7	3.0	1.7	280.0	60.0	60.0	10.4
4	33.3	5.0	3.0	426.7	75.0	30.0	7.3
5	40.0	5.0	2.3	400.0	75.0	30.0	7.3
6	40.0	4.0	1.3	373.3	90.0	60.0	8.3
7	20.0	6.0	2.3	400.0	105.0	60.0	
8	20.0	5.0	2.0	400.0	60.0	90.0	
9	20.0	6.0	2.3	400.0	90.0	60.0	
10	50.0	6.0	2.3	400.0	60.0	60.0	
11	40.0	8.0	2.3	400.0	60.0	60.0	
12	40.0	5.0	1.7	373.3	45.0	60.0	

Table 18: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 11

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	40.0	5.0	2.7	426.7	60.0	30.0	6.2
2	46.7	5.0	1.7	400.0	60.0	60.0	9.3
3	46.7	4.0	2.7	400.0	60.0	30.0	11.4
4	40.0	5.0	1.3	400.0	30.0	60.0	10.4
5	46.7	6.0	2.3	426.7	105.0	60.0	10.4
6	43.3	7.0	2.7	426.7	75.0	60.0	7.3
7	16.7	4.0	1.7	466.7	75.0	60.0	
8	20.0	6.0	2.0	373.3	60.0	60.0	
9	16.7	5.0	2.3	426.7	120.0	60.0	
10	46.7	6.0	2.3	493.3	60.0	60.0	
11	40.0	7.0	2.0	373.3	60.0	60.0	
12	60.0	9.0	2.0	426.7	75.0	60.0	

Table 19: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 12

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	30.0	4.0	2.0	373.3	30.0	30.0	6.2
2	33.3	4.0	0.7	413.3	60.0	60.0	6.2
3	36.7	4.0	1.0	400.0	60.0	60.0	6.2
4	30.0	4.0	1.7	373.3	60.0	60.0	6.2
5	40.0	6.0	3.3	373.3	90.0	60.0	6.2
6	36.7	6.0	1.7	360.0	60.0	60.0	6.2
7	20.0	8.0	2.0	400.0	150.0	60.0	
8	13.3	6.0	1.7	373.3	60.0	60.0	
9	13.3	6.0	2.0	373.3	90.0	60.0	
10	43.3	6.0	1.3	413.3	60.0	60.0	
11	43.3	6.0	1.0	386.7	60.0	60.0	
12	36.7	6.0	1.3	386.7	60.0	60.0	

Table 20: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 13

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	60.0	6.0	2.7	426.7	90.0	60.0	6.2
2	46.7	5.0	3.0	440.0	75.0	60.0	8.3
3	53.3	8.0	3.7	466.7	60.0	30.0	6.2
4	50.0	7.0	2.0	320.0	90.0	30.0	8.3
5	53.3	9.0	3.0	413.3	135.0	60.0	8.3
6	46.7	8.0	4.0	440.0	105.0	60.0	12.5
7	20.0	9.0	2.3	440.0	90.0	60.0	
8	16.7	7.0	1.7	426.7	45.0	60.0	
9	23.3	9.0	2.3	466.7	60.0	60.0	
10	46.7	12.0	3.0	413.3	75.0	60.0	
11	50.0	9.0	2.3	360.0	75.0	60.0	
12	46.7	7.0	2.0	400.0	30.0	60.0	

Table 21: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 14

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	46.7	7.0	2.7	426.7	90.0	60.0	11.4
2	56.7	4.0	2.7	386.7	90.0	60.0	9.3
3	56.7	6.0	2.7	413.3	75.0	60.0	11.4
4	40.0	5.0	4.3	440.0	60.0	30.0	13.5
5	46.7	5.0	2.3	413.3	90.0	30.0	14.5
6	56.7	5.0	2.3	400.0	60.0	30.0	12.5
7	26.7	6.0	2.0	426.7	30.0	60.0	
8	26.7	4.0	2.3	386.7	60.0	60.0	
9	26.7	5.0	3.0	426.7	75.0	60.0	
10	46.7	8.0	2.7	466.7	60.0	60.0	
11	56.7	7.0	1.7	413.3	120.0	60.0	
12	60.0	7.0	3.3	506.7	60.0	60.0	

Table 22: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 15

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	56.7	4.0	2.7	360.0	90.0	30.0	7.3
2	63.3	4.0	3.3	466.7	90.0	30.0	12.5
3	56.7	4.0	2.7	400.0	90.0	30.0	8.3
4	46.7	5.0	3.7	426.7	90.0	60.0	9.3
5	46.7	7.0	2.0	400.0	60.0	60.0	9.3
6	46.7	7.0	3.7	426.7	75.0	60.0	11.4
7	20.0	7.0	2.7	413.3	135.0	60.0	
8	30.0	6.0	3.0	440.0	90.0	60.0	
9	26.7	7.0	2.3	413.3	75.0	60.0	
10	53.3	7.0	3.3	346.7	105.0	60.0	
11	53.3	8.0	3.3	480.0	60.0	60.0	
12	60.0	7.0	2.3	440.0	105.0	90.0	

Table 23: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 16

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	43.3	4.0	1.3	426.7	60.0	30.0	11.4
2	43.3	4.0	2.0	400.0	60.0	60.0	8.3
3	36.7	4.0	2.0	400.0	45.0	60.0	9.3
4	33.3	4.0	1.7	360.0	60.0	30.0	8.3
5	33.3	7.0	1.3	360.0	45.0	30.0	12.5
6	26.7	4.0	0.7	346.7	60.0	30.0	8.3
7	20.0	5.0	1.7	360.0	105.0	60.0	
8	20.0	4.0	2.3	333.3	75.0	60.0	
9	20.0	5.0	2.0	346.7	90.0	60.0	
10	43.3	6.0	1.7	346.7	75.0	60.0	
11	40.0	7.0	2.0	360.0	60.0	60.0	
12	43.3	6.0	2.3	413.3	75.0	60.0	

Table 24: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 17

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	46.7	4.0	2.3	400.0	90.0	60.0	10.4
2	50.0	5.0	1.3	413.3	60.0	60.0	7.3
3	46.7	5.0	2.7	426.7	60.0	60.0	8.3
4	50.0	8.0	2.0	373.3	75.0	30.0	11.4
5	50.0	6.0	1.3	400.0	45.0	60.0	10.4
6	40.0	6.0	1.7	426.7	45.0	60.0	9.3
7	20.0	7.0	1.7	400.0	60.0	60.0	
8	20.0	5.0	2.3	426.7	60.0	60.0	
9	20.0	5.0	2.7	400.0	60.0	60.0	
10	40.0	7.0	2.0	413.3	60.0	60.0	
11	46.7	7.0	3.0	426.7	105.0	60.0	
12	43.3	7.0	2.0	360.0	60.0	60.0	

Table 25: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 18

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	26.7	3.0	1.3	360.0	60.0	60.0	7.3
2	23.3	4.0	1.3	453.3	30.0	60.0	10.4
3	20.0	4.0	1.3	413.3	90.0	60.0	10.4
4	26.7	6.0	1.3	400.0	90.0	30.0	9.3
5	20.0	3.0	1.3	373.3	45.0	30.0	6.2
6	20.0	6.0	1.3	373.3	60.0	30.0	7.3
7	10.0	6.0	1.3	373.3	30.0	60.0	
8	13.3	7.0	1.3	373.3	45.0	60.0	
9	13.3	6.0	1.7	400.0	45.0	60.0	
10	36.7	7.0	2.0	373.3	60.0	60.0	
11	30.0	7.0	1.3	360.0	45.0	60.0	
12	26.7	7.0	1.3	320.0	60.0	60.0	

Table 26: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 19

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	46.7	4.0	2.7	440.0	90.0	60.0	4.2
2	53.3	3.0	2.3	480.0	105.0	60.0	6.2
3	46.7	11.0	2.7	480.0	90.0	60.0	6.2
4	56.7	7.0	5.0	400.0	60.0	60.0	6.2
5	63.3	8.0	2.7	413.3	45.0	60.0	6.2
6	53.3	6.0	2.3	400.0	60.0	60.0	4.2
7	20.0	7.0	3.0	453.3	180.0	60.0	
8	20.0	11.0	3.7	453.3	90.0	60.0	
9	20.0	9.0	4.0	400.0	75.0	60.0	
10	60.0	9.0	3.3	386.7	90.0	60.0	
11	53.3	14.0	3.3	440.0	60.0	60.0	
12	53.3	7.0	2.0	386.7	90.0	60.0	

Table 27: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 20

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	60.0	6.0	2.7	373.3	75.0	60.0	8.3
2	53.3	4.0	2.0	480.0	60.0	60.0	9.3
3	53.3	5.0	2.3	533.3	45.0	60.0	10.4
4	50.0	9.0	3.0	386.7	90.0	30.0	8.3
5	46.7	8.0	2.3	506.7	75.0	60.0	7.2
6	46.7	9.0	2.7	440.0	135.0	60.0	11.4
7	26.7	8.0	3.0	400.0	75.0	90.0	
8	26.7	9.0	2.7	453.3	90.0	60.0	
9	26.7	8.0	3.3	453.3	105.0	120.0	
10	63.3	6.0	3.0	400.0	75.0	60.0	
11	63.3	8.0	2.7	493.3	105.0	90.0	
12	66.7	8.0	2.7	426.7	60.0	60.0	

Table 28: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 21

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	46.7	5.0	2.3	560.0	105.0	60.0	10.4
2	53.3	6.0	2.0	533.3	45.0	60.0	10.4
3	53.3	5.0	3.3	600.0	60.0	60.0	10.4
4	66.7	10.0	3.3	400.0	90.0	60.0	8.3
5	60.0	7.0	4.7	453.3	90.0	60.0	12.5
6	56.7	8.0	4.0	520.0	90.0	60.0	8.3
7	26.7	7.0	3.7	506.7	90.0	90.0	
8	30.0	7.0	2.7	506.7	90.0	90.0	
9	30.0	9.0	2.7	533.3	60.0	90.0	
10	66.7	6.0	3.0	560.0	75.0	90.0	
11	53.3	8.0	2.3	466.7	60.0	60.0	
12	60.0	8.0	2.0	440.0	45.0	60.0	

Table 29: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 22

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	40.0	6.0	2.7	466.7	60.0	60.0	8.3
2	40.0	4.0	1.7	453.3	15.0	60.0	8.3
3	40.0	2.0	2.0	453.3	30.0	60.0	7.3
4	33.3	6.0	4.0	373.3	135.0	30.0	8.3
5	40.0	7.0	4.0	373.3	120.0	30.0	7.3
6	33.3	6.0	4.0	426.7	120.0	30.0	7.3
7	20.0	5.0	1.7	413.3	90.0	90.0	
8	20.0	6.0	2.3	440.0	120.0	90.0	
9	16.7	8.0	2.3	453.3	90.0	90.0	
10	43.3	7.0	3.3	413.3	90.0	60.0	
11	43.3	4.0	2.3	400.0	60.0	60.0	
12	43.3	4.0	2.0	426.7	90.0	60.0	

Table 30: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 23

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	43.3	6.0	3.3	466.7	60.0	60.0	8.3
2	46.7	5.0	2.0	453.3	90.0	30.0	8.3
3	43.3	4.0	4.3	506.7	120.0	60.0	9.3
4	46.7	7.0	2.0	386.7	60.0	60.0	8.3
5	53.3	7.0	1.3	480.0	90.0	30.0	7.3
6	46.7	7.0	1.3	480.0	90.0	60.0	7.3
7	16.7	8.0	1.3	426.7	90.0	60.0	
8	20.0	6.0	3.0	453.3	75.0	60.0	
9	16.7	7.0	2.0	453.3	60.0	60.0	
10	46.7	7.0	1.7	493.3	60.0	60.0	
11	46.7	10.0	2.7	453.3	60.0	60.0	
12	43.3	10.0	2.7	480.0	90.0	60.0	

Table 31: Maximum experimental values of forces (lbs), torques (in-lbs), and acceleration (ft-sec^2) for condition 24

Trial	Vertical Force	Frontal Force	Lateral Force	Somersault Torque	Cartwheel Torque	Twist Torque	Acceleration of Object
1	20.0	4.0	1.0	440.0	45.0	60.0	10.4
2	33.3	5.0	1.3	386.7	90.0	60.0	7.3
3	33.3	6.0	2.0	413.3	60.0	60.0	8.3
4	30.0	5.0	1.7	440.0	60.0	60.0	6.2
5	33.3	6.0	1.7	400.0	120.0	60.0	7.3
6	40.0	5.0	1.7	386.7	60.0	30.0	9.3
7	20.0	6.0	1.7	453.3	90.0	60.0	
8	16.7	7.0	1.3	426.7	45.0	90.0	
9	16.7	8.0	1.6	400.0	75.0	60.0	
10	40.0	8.0	2.0	400.0	90.0	30.0	
11	43.3	10.0	1.3	400.0	90.0	60.0	
12	36.7	8.0	1.7	426.7	90.0	60.0	

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FORCE EXERTION DURING SQUAT LIFTING WITH LIGHT LOADS

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ABSTRACT

A dynamic analysis was performed for a lifting task to gain an insight as to the variables affecting force exertion during occasional lifting. Also from the analysis, formulas were developed to predict the maximum resultant forces on three orthogonal axes and the torques around these axes.

To test the ability of the formulas to predict accurately, a lifting experiment was performed and the resultant forces and torques were measured by a force platform.

The experimental results revealed the theoretical formulas to be only fair predictors. However, statistical tests on the empirical data showed a significant influence for several of the variables as designated by the theoretical analysis.