FORCES AND TORQUES INVOLVED IN LIFTING

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Approved by:

Major Professor

"To my parents"

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INTRODUCTION

The ability of man to lift and handle heavy loads distinguishes him strongly from most other vertebrates. One of the most important problems of work physiology is to determine whether a man's work may be considered as normal or an overload. In manual material handling, man is limited by both his skeleto-muscular system and his cardio-respiratory system. Man's skeleto-muscular system limits the amount of weight that he can handle at infrequent intervals. Man's cardio-respiratory system, on the other hand, limits the amount of weight if the task is frequent. In spite of the practical importance of the subject of human weight lifting, and in spite of the sporadic attention which the subject has received over a long period of time, surprisingly little is known about this area. From experiments, facts have been established as to the maximum lifting weight for men, women and boys and, based on these and subjective judgement, some rules of thumb exist about limits which people should be allowed to lift.

An important aspect of the subject of weight-lifting operations is the risk of structural injury - in particular to the skeletal-musculo structure of the back. According to a study made by Brown (1958), approximately 25 percent of handling accidents are due to lifting. Work has been done in investigating the reason of back injuries, but very little seems to be known about the forces and torques that cause back injuries.

The six forces and torques involved in the lifting of a weight are the frontal, lateral and vertical forces and the torques about these three axes. If safe conditions are to be defined, the nature of these forces and torques and their relation to the different sizes of human beings must be studied.

In lifting, the greatest force seems to be on the spine. The spinal column supports the trunk and head, envelops and protects the spinal cord and participates in every movement of the limbs. It consists of 25 bony vertebrae, separated by semi-cartilaginous discs to give the spinal column its flexibility and mobility. The parts of the spine that are of most interest are: 1) the vertebral bodies and discs, because they are the primary weight bearing components, 2) the spinal muscles, because they support the spine, and 3) the abdomen, which, though not a part of the spine, is an aid as it provides support to the spine. Other components are the neural arch, articular processes, transverse processes, and spinous processes which, of course, are important to the function of the spine but have been reported to be involved in relatively few injuries due to lifting. Without a doubt the most complicated parts of the back, not only anatomically but with respect to injuries, are the intervertebral discs.

Two types of lifting are generally used - a "bend" and a "squat". "Bend" is defined as bending over from the waist, with the legs kept straight at all times, lifting the weight, and placing it on a shelf. "Squat" is defined as lifting by bending the knees and keeping the back relatively straight. A "squat" is the recommended lifting procedure while a "bend" is not recommended. Squatting is recommended because, with this technique the trunk bends from the hips and not from the lumbar vertebrae, the back is relatively straight and the spinal discs are placed under an even and moderate strain.

Persons with small vertebrae dimensions require a greater amount of muscular tension for a given lifting activity than persons with large vertebrae. Therefore, the small-vertebrae persons are subject to greater amounts of muscle exhaustion and eventual strain.

All load lifting jobs should be well defined in terms of physical demand. Proper lifting techniques and the selection of the correct individual for the job are important factors in back disorders. The risk of injury is particularly great when excessive strain is combined with degenerative changes in the back that are caused by advanced age or pathological disturbances.

Lifting tasks can be subdivided into two categories: 1) An average high energy expenditure level (e.g., lifting a 22 pound load 100 times/shift) which is limited by cardiac and respiratory organs. 2) Low average energy expenditure level but a high peak load (e.g., lifting a 145 pound load once per shift). This type could also be described as not-repetitive, short duration lifting. The peak load is probably limited by the skeleto-muscular system. In this thesis, the author studied the second type of lifting with small loads. In order to analyze the effects of the forces and torques on the spine when a "lift" is made and thereby establishing safety standards for lifts for different percentiles of the population, it is essential to know how different parameters of the lifting tasks are related to the various forces and torques.

LITERATURE REVIEW

Previous work has been done on lifting. Unfortunately, hardly any work has been done with the same objective as the author's and therefore little information is available which is directly relevant. To the best of the author's knowledge, this research is the only one on lifting involving torques. However, a literature survey consisting of related facts has been made to enable the reader to obtain a better background and stimulate interest in this particular field.

Whitney (1958) conducted a study on the maximum lifting force exerted by a subject under a variety of lifting conditions on eight subjects. Whitney's variables were: reaching distance, bar height, type of grasp, and bending vs. squatting. For the particular ranges of the variables selected, he concluded that the most important variable determining the maximum lifting force is the distance of the feet from the frontal plane including the grasp axis. The maximum lifting force decreased rapidly with increase of this distance. The maximum lifting force also decreased with increase of grasp height, but the influence of grasp height was much less than that of foot placement distance. Whitney's study, however, was not made of an actual lifting task and the force platform he used was rather insensitive as compared to Hearn's (1968).

Switzer (1962) studied the weight lifting capabilities of human males. The task was to lift a weight from the floor, without strain, to three different platform heights (18 inches, 42 inches, and 62.5 inches) with three different positions of lifting. Significant differences were found for platform heights, with the weight limit decreased with the increased height of subjects. However, no significant differences in lifting capacity were found for the three lifting positions.

Snook and Irvine (1965) investigated the maximum weights and work loads acceptable to male industrial workers while performing lifting, lowering, pushing, pulling, carrying and walking tasks. For all tasks, subjects were instructed to adjust their work load to the maximum amount that they could perform without strain or discomfort, and without becoming tired, weakened, overheated, or out of breath. The maximum loads for "lift" and "lower" were found for the different heights of the male workers. The maximum weight for floor level to knuckle height "lift" for 90th percentile height was 70.3 pounds and for 10th percentile height was 37.3 pounds. For "lower" the maximum varied from 36.2 pounds to 87.6 pounds. Similarly, the maximum weight for knuckle height to shoulder height "lift" varied from 34.4 pounds (for the 90th percentile) to 70.9 pounds for (10th percentile), and for "lower" the values ranged from 39.2 pounds to 70.2 pounds. Values for shoulder height to arm reach "lift" ranged between 29.4 pounds to 68.3 pounds, for "lower" it was 28.7 pounds to 59.9 pounds.

Damon (1966) concluded from his study that less powerfully built persons, however, may be more efficient in performing the frequent, repetitive lifting tasks, where lifting frequency or work load is often the limiting factor.

Stueve (1968) studied the physiological cost of lifting and lowering a 25 pound tote pan. Three orthogonal forces were measured by a force platform for bending versus squatting. For the lifting procedure studied, Stueve found that the physiological cost is less in a bending manner than a squatting manner. He also concluded that the physiological cost for lowering an object is greater than for lifting it.

Snook (1970) investigated the effect of increasing age on work capacity, and whether physique has a greater effect on continuous work capacity during slower, heavier tasks, than during faster, lighter tasks. He concluded that continuous work capacity does not decrease with age. The idea that physique has a greater effect on continuous work capacity was supported only by the results of the younger groups of subjects.

Back Injuries.

Since this thesis is concerned at least inferentially with back injuries, a brief review of the extensive literature on back injuries is in order.

Wayne (1954) and Ruseek (1955) made statistical inquiries and established the high number of back injuries in tasks involving weight lifting. According to Armstrong (1965), Morris, Lucas, Bresler (1961), and Nachemson (1962), injuries to the spine in lifting seems to be concentrated on the vertebral bodies, intervertebral discs and soft tissue, that is, muscles and ligaments.

Since the occurrence of injury to the lower back is so common, it has given rise to specific safe methods of weight lifting (Ministry of Labor and National Service, 1944), Anderson (1951), Cyriax (1954), and Floyd and Silver (1955). It was found that lifting by bending the trunk, with the knees kept straight, is dangerous compared with the method of lifting which involves flexed knees and an upright trunk ("knee-action"). Floyd and Silver proved that the "knee-action" method minimizes strains to the posterior ligament of the spine. Das (1951) found that the relative metabolic efficiencies of the two methods of lifting varied with the magnitude of weight lifted.

Thieme (1950) concluded that the low back or lumbar region is the main area where spinal injuries occur. One study on herniation of intervertebral discs, often referred to as "slipped disc", indicated that 97 percent of the herniations occur in the lumbar region. In fact, 89 percent were in the lowest two lumbar discs which are situated between the L-4/L-5 and L-5/S-1 vertebral bodies. Perey (1957) established that the compressive strength of vertebral bodies ranges from about 1180 to 1800 pounds/square inch for the under forty group and from 420 to 690 pounds/square inch for the over sixty group.

Morris (1961) demonstrated that, when a subject is holding 200 pounds with the trunk flexed sixty degrees from the normal standing position, and with the arms hanging straight down, the force on L-5/S-1 disc is approximately 1400 pounds. Sonoda (1962) estimated that the fracture load for women is 5/6 of that for men. He also found that no difference in strength per unit area of the spinal column existed between men and women. This indicates the difference in strength is due to the difference in surface area of the vertebral bodies.

Troup (1965) studied back injuries in industry, back pains caused by lifting or twisting movements. He concluded: 1) Only a small proportion of low-back disorders can properly be attributed to accidents. 2) Heavy manual work is a major contributory factor. 3) In men engaged in heavy work, the prevalence of lumbar vertebral degeneration is higher, low back disability is more common and causes more incapacity than in those engaged in light work.

Ticheauer (1965) studied the biomechanics of the arm-back aggregate under different working conditions. The study clearly demonstrated the importance of horizontal distance between the weight and the spine, and manual lifting from an awkward working position or with poor posture may cuase excessive force upon the vertebrae even when lifting relatively light loads. He suggested that lifting tasks should be so designed that the compressive stress acting at the intervertebral discs of the lumbar spine should be kept well below 1500 pounds.

Fine (1966) developed a model to predict the compressive force against lumbrosacral disc. The external forces he considered were the weight of the head, neck and arms, weight of the trunk above the lumbrosacral disc, and the weight of the object lifted, all weights acting through their respective center of gravity. The resisting interval forces were the intensity of intro-abdominal pressure times effective abdominal cross-section, the tension in the deep muscles of the back, and the reaction on the lumbrosacral disc. For one particular person lifting a 90 pound weight, Fine calculated a compressive force of 1000 pounds on the disc. He also pointed out that a 20 pound part lifted 40 inches in front of the operator was equivalent to a 59 pound weight in upright position (700 pounds on the disc).

Chaffin (1967) developed a biomechanical model to predict 1) reactive forces and forces on the L-4/L-5 disc and on the L-5/S-1 disc, 2) translation of the reactive forces to normal (compressive and tangential, shear, forces on the superior surfaces, of the S-1 and L-5 vertebral bodies and on the inferior surface of the L-4 and L-5 vertebral bodies.

Chaffin and Baker (1970) developed a model of the human body. It assumed the skeletal muscle system to be analogous to a series of eight solid links representing the major body segments. The model was restricted to symmetric, sagittal body-plane activities. This model could evaluate various static situations, such as when one is holding a weight or pushing or pulling. In addition, the model could be used to analyze slow moves, such as when lifting a heavy object, by formulating the input data so as to describe a sequence of static positions. This type of a model represents a rational method for investigating the many variables that affect the physical strength capability of any individual required to perform material-handling activities.

Force Platforms.

For years industrial engineers have been concerned with the motions an individual makes in performing a task as well as the forces exerted during the motions. Various techniques have been used to study the motions, including film methods such as cyclegraphic and chronocyclegraphic analysis. Until about 1949, however, very little had been done toward making an analysis of the forces exerted by an individual in the performance of a task. One of the earliest devices for studying these forces was the "Effort Detector" developed by a Frenchman, Lucein Lauru (1953). Lauru improved upon his platform in 1957, when he made use of the piezo-electric properties of quartz as a force detector. The variations in force applied to the quartz produced variations in electric current in an external circuit connected to the quartz crystal. This variation of current was then displayed on an oscilloscope; a permanent record was made by photographing the traces. Lauru did not report evidence that the proposed measure of bodily movements was in fact a measure of physiological cost. However, he did imply from his studies that the larger the force expenditure, the more effort required for the given task (Lauru, 1957).

Greene (1957) was the first to develop a force platform in the United States and to take a sophisticated approach to the problem of interpretation of the results obtained from a device of this type. Greene used linear variable differential transformers (LVDT) connected to a conventional strip chart recorder. He supported his triangular platform on three cantilever beams. The triangular design and the arrangement of the beams enabled three transducers to sense separately the frontal, vertical and transverse components of an applied force. The deflection of a cantilever beam is directly proportional to the applied force which, in turn, is converted into electrical voltage by means of the LVDT and is recorded on the chart.

Jacobson (1960) made a dynamic evaluation of a force platform. The force platform had sufficient sensitivity to measure one-half pound force in the frontal axis and one pound force in the lateral axis. He concluded that this minimum force sensing capability was unaffected by frequencies of force application from 50-200 cpm or by variation in subject weight from 100 to 200 pounds.

In 1964 Greene's platform was improved by Barany and Whetsal (Whetsal, 1964). They used three additional cantilever beams to preload the three beams acting upward so that the forces acting up as well as those acting down could be detected. The three additional beams were supported at the tips of a second triangle rotated 60 degrees with respect to the first, making a hexagonal shaped platform.

A major improvement, torque measurement about the three axes, was introduced by Konz and Hearn (Hearn and Konz, 1968). Two extra LVDT's for each axis were placed on the lower platform with their lines of action located an equal distance on either side of the torque axis. The lines of these transformer cores also lie in a plane which is perpendicular to the associated axis. The electrical connection of the two transformers is such that any variation of the position of one transformer relative to that of the other will give a resulting output. If both cores move along their lines of action by the same amount, there is no output signal.

Application of Force Platforms.

Several investigations have been carried out on the force platform since Lauru's work in 1957.

Barany (1963) investigated the nature of individual differences in bodily forces on subjects performing a simple motor task. He concluded that (i) A very large portion of the variation in the amount of force exerted per cycle can be attributed to individual differences. (ii) There was no significant relationship between any one anthropometric measurement and the average amount of force exerted for each cycle of the task.

Barta (1962) investigated the existence of a relationship between the external force (measured by the force platform) exerted by a worker and time as the criterion for work measurement. He found that the three components of external force, measured by the force platform, increased at a much greater rate than the increase in time as the weight handled increased from 0.35 to 12.92 pounds.

Dunnington (1961) and Hudson (1962) studied the effect of work place dimensions on the physical cost as measured by the force platform. The task contained a variety of motions and simulated a drilling operation. They found that adjusting the work place to fit the subject's anthropometric measurements significantly reduced the effort (force expenditure in lb. - sec.) to perform the task.

Wu, 1965, (also Konz, 1967) investigated the effect of direction of movement and height of the work station. The seated subject moved a two pound weight with the right hand from a central point to a peripherial point 15 inches away; five different heights of work station and five different angles were considered. Physical cost as measured by the force platform was used as the criterion. Wu found that an optimum vertical distance was at 0.85L, L being the length of the upper arm of the individuals.

Jeans (1966) studied the physical cost of simultaneous and symmetrical motions. The subject moved a two-pound weight in each hand between specified points 18 inches apart. It was concluded that the outward motions of both hands required more force than the inward motions.

Stueve (1968), as mentioned, studied the physical cost of lifting and lowering a 25 pound tote pan. The orthogonal forces were measured for bending versus squatting. For the lifting procedure studied, Stueve found that the physiological cost is less in bending manner than a squatting manner. He also concluded that the physiological cost for lowering an object is greater than for lowering it.

Sankaran (1968) studied the optimum height of a work table for simple arm movements while sitting. The criterion used was the physical cost as measured by the force platform. Ten female subjects were used and five heights (+1.2, 0, -1.2, -2.4, -3.6 inches from the elbow) were studied.

The work table height at three centimeters below the elbow level required the minimum physical cost while the table level set at nine centimeters below the elbow required the maximum cost. It was found that there was a significant difference between the inward and outward movements, the outward having less cost than the inward for the table heights below the elbow level. But for the table heights above the elbow level, the inward movements required less physical cost than the outward movements.

PROBLEM

As can be seen from the literature survey, research has been done in the field of lifting on back injuries and on forces produced in lifting, but no experimentation has been done so far which connects both lifting forces and torques produced and back injuries resulting thereby finding load limits for lifting under various conditions without causing back injuries. This research is a first step toward these relationships since the main aim is to examine the behavior of the three parameters, distance, weight and angle of turn. These three parameters are discussed later in this section.

The safe limits for the weights of the load, the distance of the center of the load from the spine, etcetera, for different conditions of lifting and for the various ranges of populations, could be found by running an experiment where values of lifting parameters were increased to the point where the subject's back is injured. Of course, this approach of injuring a subject in order to find the upper limit of the safety region is not an ethical approach.

A better approach would be to make a mathematical equation or a set of equations in terms of the three parameters studied here. This would predict (within a reasonable degree of accuracy) the stress on the L-5 disc for a particular task. By studying the trend of the values obtained from such models, the maximum load points for each of the three parameters could be found. By applying a reasonable factor of safety to such points, the safety regions could be established.

The importance of the horizontal distance between the center of load and the spine has been demonstrated by Whitney (1958), by Tichauer (1965) and by Fine (1966). For any lifting task, according to physics, the weight of the load should also be an important parameter. If the task involves a body turn, the angle of turn should also play a part in the model. Therefore, in order to find the limiting conditions of the stress on the spine with respect to safety for any average lifting task, parameters of major concern would be the weight of the load, the distance of the center of the load from the spine, and the angle of turn of the spine (assuming that the body turns through the same angle as the spine). However, even before one can think of working on a mathematical model from which the limiting conditions could be found and thus employing safety limits, the very first step should be to define and investigate the nature and the behavior of the parameters of a typical lifting job.

This is the problem investigated and analysed for this thesis. As mentioned already, for any lifting job there are three very important and dominating parameters involved.

The "distance" is the distance from the spine to the center of the weight placed in front of the body. Distance is measured on the horizontal plane and is maintained positive for all conditions of lift. In this research, it has been assumed that when standing straight, the spine and the back of the heels are on the same vertical line. Therefore, the distance of the center of the load from the spine would also equal to the distance of the center of the load to the back of the heel. It was the latter distance that was used in the research.

The "weight" of the load is the weight of the object lifted by the subject.

The "angle" of rotation is the amount of turn the spine rotates through during the task. The rotation takes place clockwise or counterclockwise. The reference position was when the subject had his face, chest, trunk and toes pointing straight ahead.

The three forces involved in a lifting task are; frontal, vertical and lateral force. The three torques involved are; twist, somersault and cartwheel. All the forces and torques act along and about three orthogonal axes. Figure 1 shows the three orthogonal axes, X, Y, and Z.

The Z axis is the vertical axis and is parallel to the spine. Therefore, it is perpendicular to the plane including the feet of the person. The weight of the load acts along the spine and is therefore parallel to the Z axis. The force parallel to the Z axis is called the "vertical" force. The torque about the Z or vertical axis is called the "twist". The twist could be clockwise or counterclockwise, depending upon the direction of rotation.

The Y axis is the frontal axis. The frontal axis is perpendicular to the plane passing through the subject's shoulders. Therefore, the frontal axis is perpendicular to the chest. The force along the frontal axis is called the "frontal" force. The frontal force can act from the front or back of the subject. The effect of such a force would be to move the subject backward or forward. The torque about the frontal axis is called "cartwheel". The cartwheel torque could be clockwise or counterclockwise.

The X axis is the lateral axis. The lateral axis lies in the same plane as the frontal axis, but is perpendicular to the latter. This force along the X - axis is called the "lateral" force. The lateral force is perpendicular to the lateral plane of the body. The effect of the lateral force would be to make the subject move sideways. The torque about the lateral axis was called "somersault", which could also be clockwise or counterclockwise depending upon the position of the load.

The forces and torques were determined as a function of angle of body twist, distance from the spine and weight of the load.

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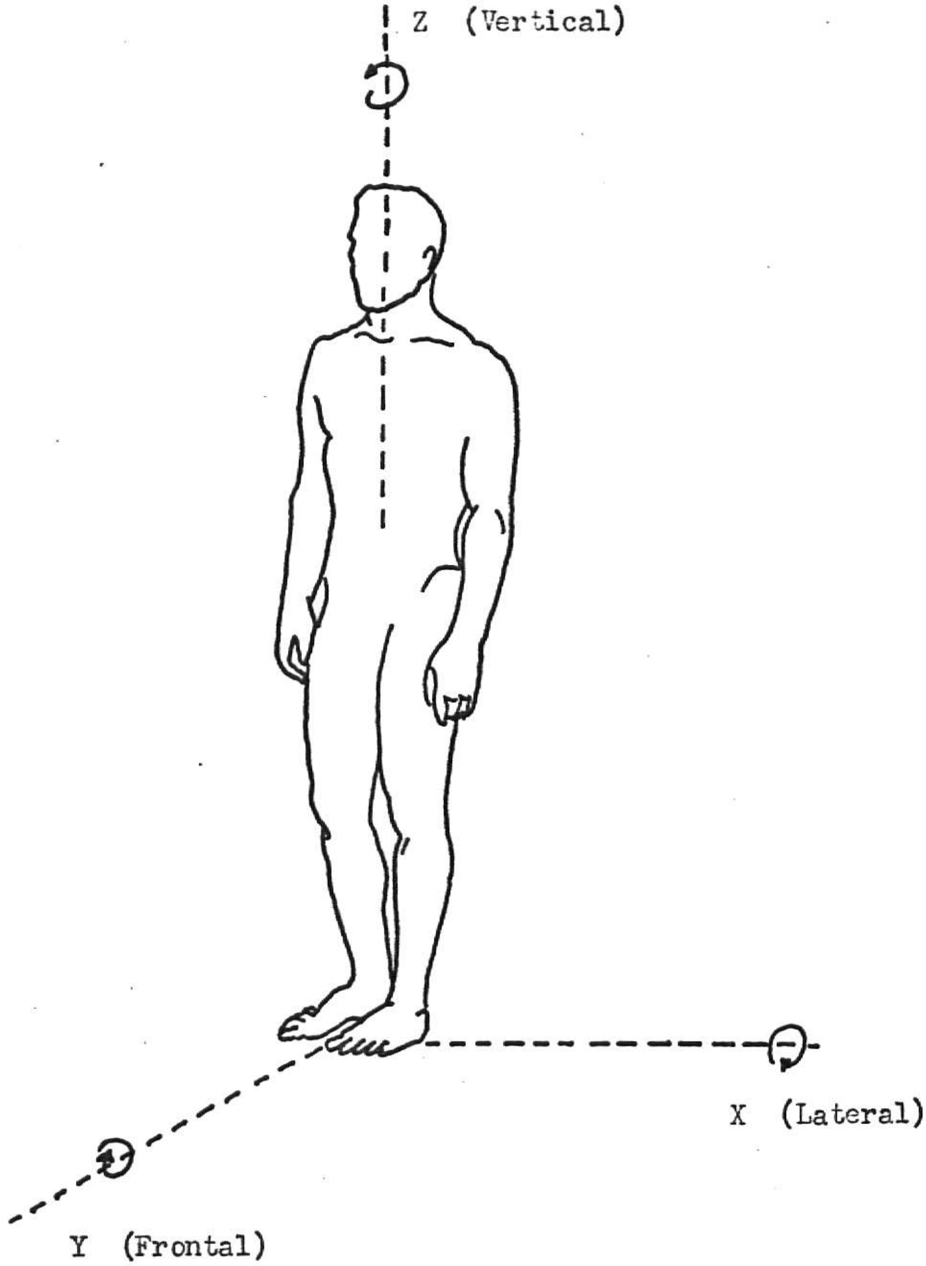

Figure 1. The three orthogonal axes with respect to the body.

The principal experimental questions investigated were:

Time or Replicate Effect. This was to see if there was a difference in performance between the two repetitions of the task. If the performance improved, it would be concluded that there was a learning effect.

Change in Angle, Weight or Distance Effect. The significance of the three main effects, weight, distance, angle and their interaction were tested for each of the three forces and the three torques corresponding to the three orthogonal axes.

It should be emphasized that this research was a study of lifting, not lifting and carrying. Also, this study, by no means was an optimization study on the three main effects. In other words, the goal was not to determine the best distance or angle to minimize physical effort, instead it was an attempt to investigate and explore the nature of the forces and torques in relationship to the parameters already mentioned by choosing values of weights, distances and angles which are representative of industrial tasks.

METHOD

Experimental Arrangement.

The experimental arrangement is shown in Figure 2. The apparatus for the experiment mainly consisted of the following:

A. Force platform.

B. Three two-channel Texas Instrument Oscillograph recorders.

C. Platform to place the load at the start of lifting.

D. Shelf to place the load at the end of the lift.

E. Standard weights.

F. Tote boxes.

G. Stop watch.

H. Bed.

The force platform used in this experiment was the KSU force platform (Hearn and Konz, 1968). The platform was calibrated at the beginning of the experiment and before each session. The force x time output of the platform for each of the orthogonal axes and torque x time output for the torques about each axis obtained was the data used for the research.

Three two-channel recorders were used to record forces on three perpendicular axes and their associated torques. The force trace originates from an established "zero" or "datum" mark and deviates up or down. The distance deviated is directly proportional to the force or torque exerted in the specific plane.

Figures 3 and 4 show the strip chart recorder of output during a lifting and lowering procedure. The pen deflection from the base line can be measured and, if multiplied by the calibration factor, will give the actual

Figure 2. Experimental set up.

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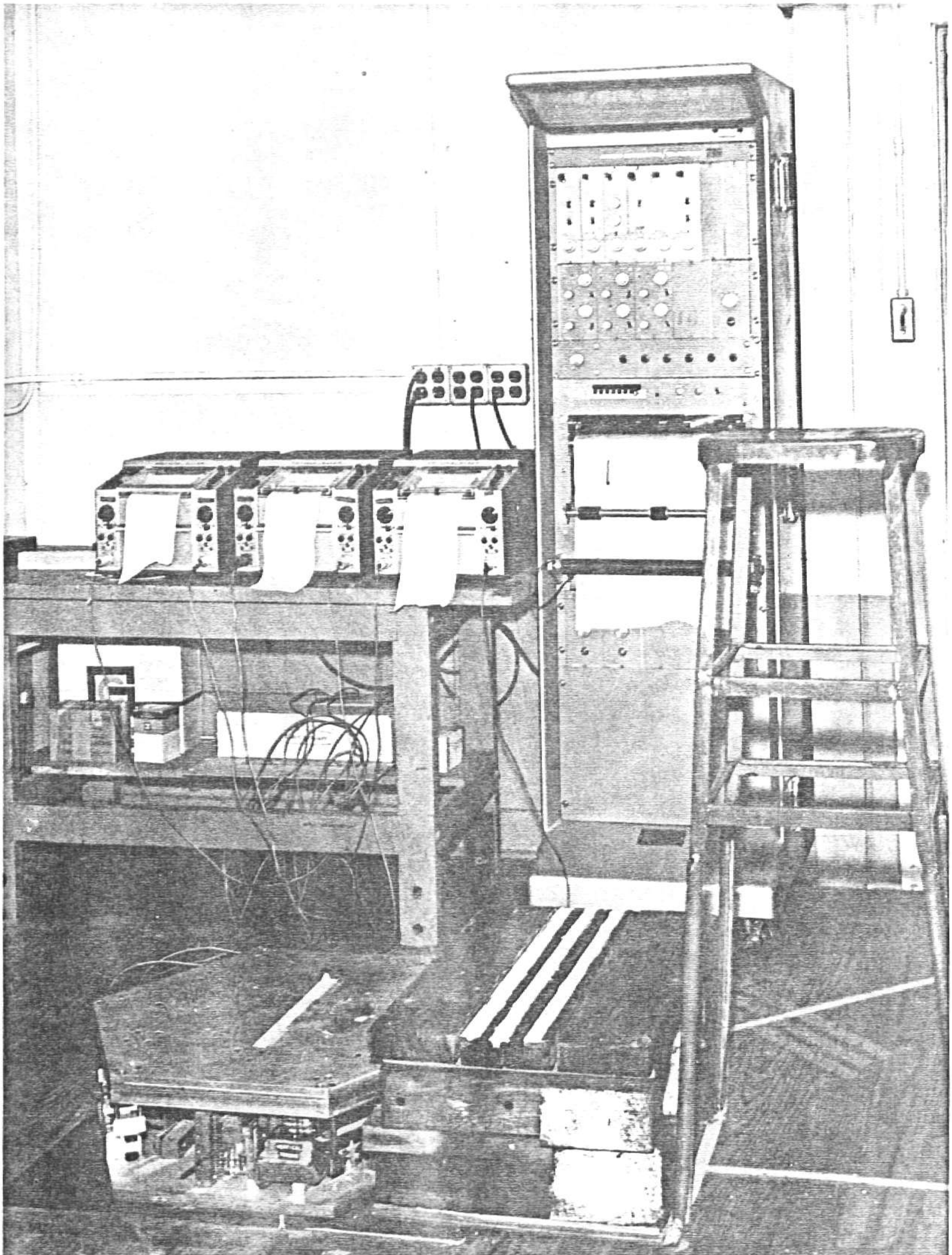


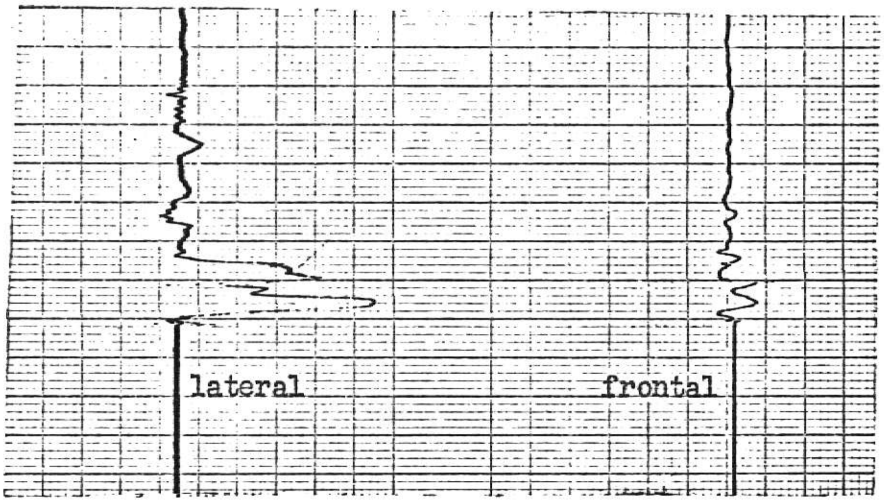


Figure 3. Sample output of recorder for lateral and frontal forces.

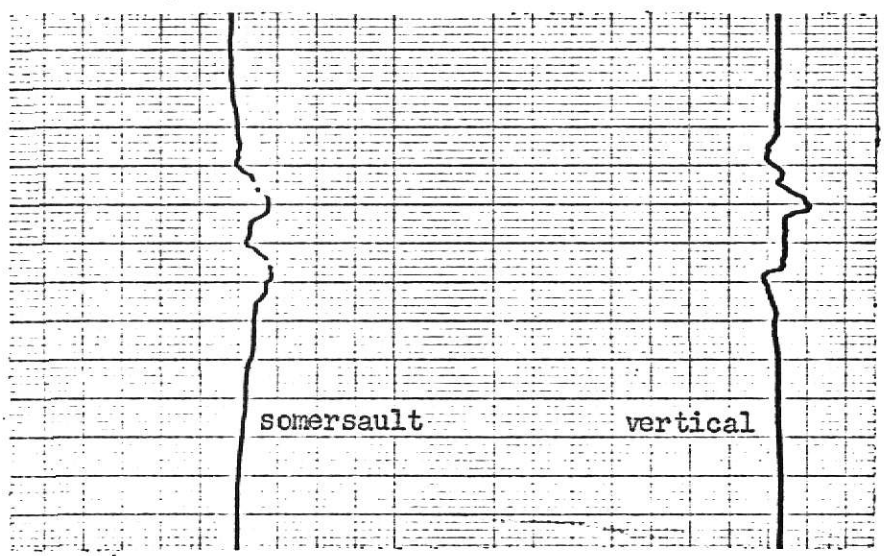


Figure 4. Sample output of recorder for somersault torque and vertical force.

force or torque. The "base line" or the "datum line" is the line that is recorded when the subject is standing still on the platform and is not performing any task. There are three axes and six forces and torques which can be obtained from the output.

For the vertical axis, if the force line is above the base line, this means that the force acting downward on the platform is greater than the force acting upward. If the force line is below the base line, the force acting downward on the platform is lesser than the force acting upward.

The torque about the vertical axis is "twist". If the twist line is above the base line this means a twist to the right, and if the twist line is below the base line, then the twist is to the left.

For the lateral axis, if the force line is above the base line, more force is applied by the right side of the subject than is applied by the left side. If the force line is below the base line, more force is applied by the left side of the subject than is by the right side.

The torque about the lateral axis is called "somersault". If the somersault torque is above the base line, the torque is being applied toward the front, if the somersault torque line is below the base line, the torque is being applied toward the back.

For the frontal axis, if the force line is above the base line, more force is applied by the front of the foot than is applied by the heel. If the force line is below the base line more force applied by the heel than the front of the foot.

The torque about the frontal axis is called "cartwheel". If the cartwheel line goes above the base line, the cartwheel is being applied towards the left hand side; if the cartwheel line is below the base line, it is being applied to the right hand side. In all cases, the physiological cost index for each of the six axes is represented by the area under the curve, and the peak heights represented the peak forces or torques. In this research, the author's interest was not in the area under the curve, but only the peak heights.

A platform was used to place the tote box on, at the beginning of the task. The platform has been called "load platform" and can be seen on Figure 2. The platform is four inches above the force platform or the plane of the feet. Three lines have been marked on the platform. The line closest to the force platform is 16 inches from the center of the force platform. The other two lines are 18 inches and 20 inches from the center of the force platform.

At the end of the task, the load was placed on a shelf. The shelf is in the form of a high stool as shown in Figure 2. The top of the shelf was 38 inches from the load platform and 42 inches from the top of the force platform. The edge of the shelf was always kept at 28 inches from the center of the force platform. The tote box was therefore always lifted through a vertical height of 38 inches.

Tote boxes were used for lifting. Three different tote boxes of 11, 22, and 33 pounds were used in this experiment. The dimension of each tote box was $16\frac{1}{2}$ x 13 x 6 inches.

A stop watch was used to measure the rest interval between conditions of lift.

An ordinary light weight bed was used for the subject to rest on, after he had finished lifting for one condition.

Design of Experiment.

As described, the three major variables investigated were

angle or turn of body, degrees,

horizontal distance of weight from back of heels, inches,

weight lifted, pounds.

In the choice of values of these parameters, attempt was made to make the task representative of most industrial lifting cases. That is, it was felt that these were used weights, distances and angles.

Every lift was a combination of the three parameters. Each combination was called a "condition". From a pilot study, it was that 15 of the 27 possible conditions would be sufficient in order to study the behavior of the forces and torques. For example, "condition 1" was a task where the distance was 18 inches, the angle of turn was 45 degrees, and the weight was 22 pounds. The 15 conditions of lift have been listed in Table 1 and have been represented on three orthogonal axes in Figure 5.

Five subjects were used in the experiment. Each of the five subjects served in each of the 15 conditions. Each condition consisted of four lifts. Therefore, for every replicate, a subject lifted 60 times in order to complete the 15 conditions. In order to obtain a better average of the forces and torques, the experiment was run in two replicates.

Experimental Procedure.

The experiment was set up and performed in the Human Engineering Laboratory at the Kansas State University.

The experimental set up was as shown in Figure 2. A weight of 170 pounds (weight of the heaviest subject) was placed on the force platform and the calibration of the force platform was then made for the one hundred seventy

TABLE 1

List of Fifteen Conditions of Lift.

Condition	Distance (inches)	Angle (degrees)	Weight (pounds)
1	18	45	22
2	20	0	11
3	20	90	11
4	20	90	33
5	20	0	33
6	16	0	11
7	16	90	11
8	16	90	33
9	16	0	33
10	18	0	22
11	20	45	22
12	18	90	22
13	16	45	22
14	18	45	11
15	18	45	33

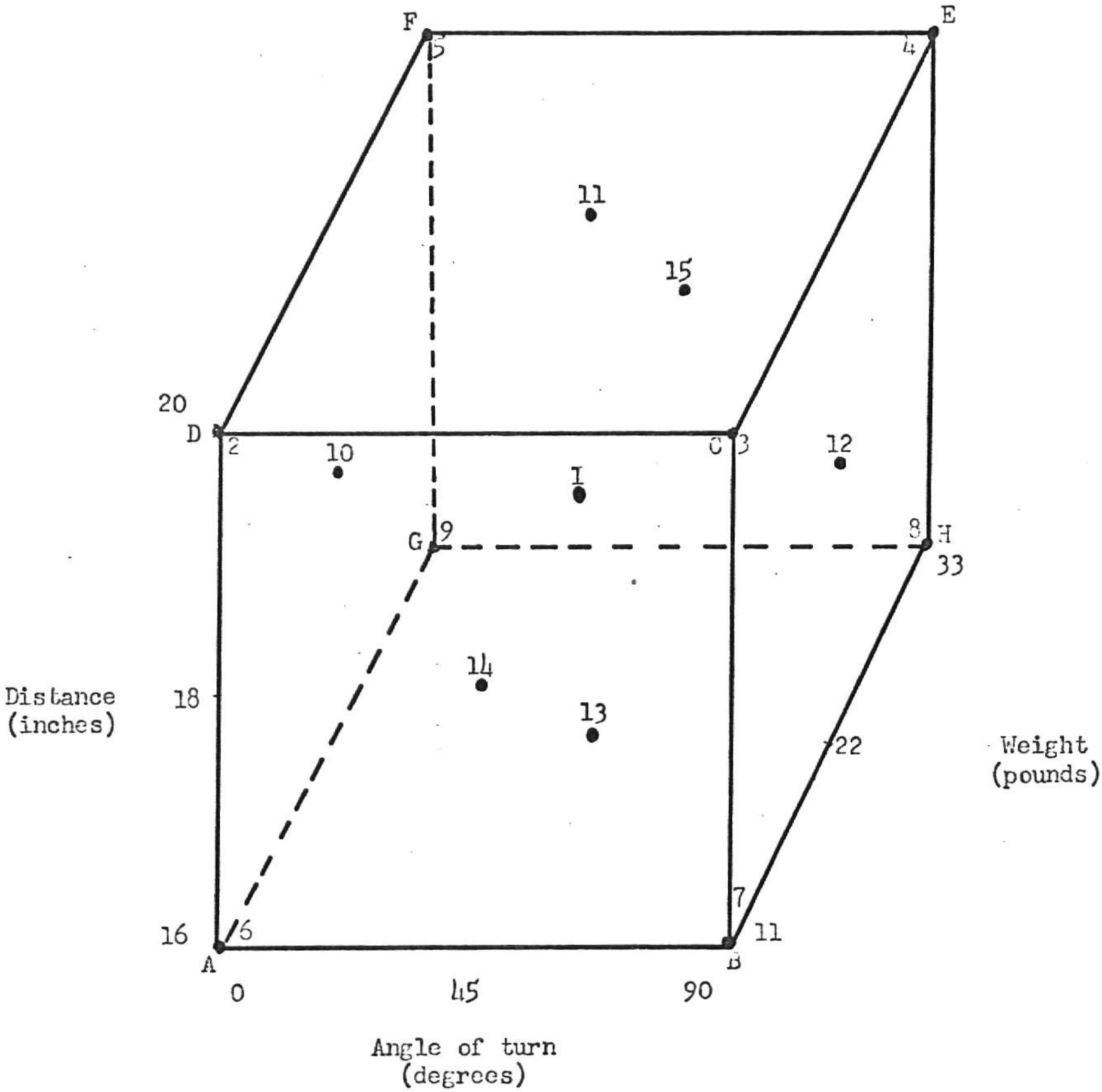


Figure 5. Cube illustrating the positions of the fifteen experimental conditions.

pounds, standard weight. Each subject was weighed and when he stood on the force platform, additional weights were placed on the platform to bring the total weight on the platform to 170 pounds. This eliminated the requirement of adjusting the transformers for each individual subject's weight. By calibration with known weights, the scale factors, which give the amount of force in pounds/millimeter of deflection on the output paper for the force axes and the torque in inch-pounds per millimeter of deflection on the output paper for the torque axes, were determined for each axis.

The subject was told the purpose of the experiment. He was asked to complete a data sheet giving information about himself. Measurements of height, weight, upper arm length, forearm length and forearm circumference were taken (Table 2).

Next, the task was defined and explained to the subject. At first, the task was shown on the television screen with the help of a pre-recorded video tape. The subject was then orally instructed about the same task and any of his questions were answered.

At the beginning of every lift, the tote box was placed on the load platform and directly in front (0 degrees) of the subject. The center of the tote box would be on one of the three lines (16 or 18 or 20 inches to the center of the box from the back of the heels). The shelf was placed at 0, 45 or 90 degrees. The weight of the box, the distance of the box, the angle of the shelf depended on the condition of lift that was being performed. For all lifts the subject had to squat, that is, he started with his feet together, then bent his knees while keeping the back as straight as possible, grasped the box with both hands, straightened up while he kept his back straight as he lifted (Figure 6) and placed the box on the shelf at 0 degrees (Figure 7) or at 90

TABLE 2

Anthropometric Measurements of Subjects.

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Age	23	26	28	24	23
Height	5' 9 3/4"	5' 9½"	5' 8"	5' 10"	5' 8½"
Weight	162 lbs.	150 lbs.	170 lbs.	152 lbs.	152 lbs.
Elbow height	44"	43½"	46"	44"	41½"
Forearm length	9½"	13"	13"	11"	10¼"
Forearm circumference	12"	11½"	12½"	9½"	10"
Upper arm length	10½"	14½"	13"	11"	13"
Upper arm circumference	10½"	10½"	13½"	10"	11"

Figure 6. The initial stage of lifting with bent knees.

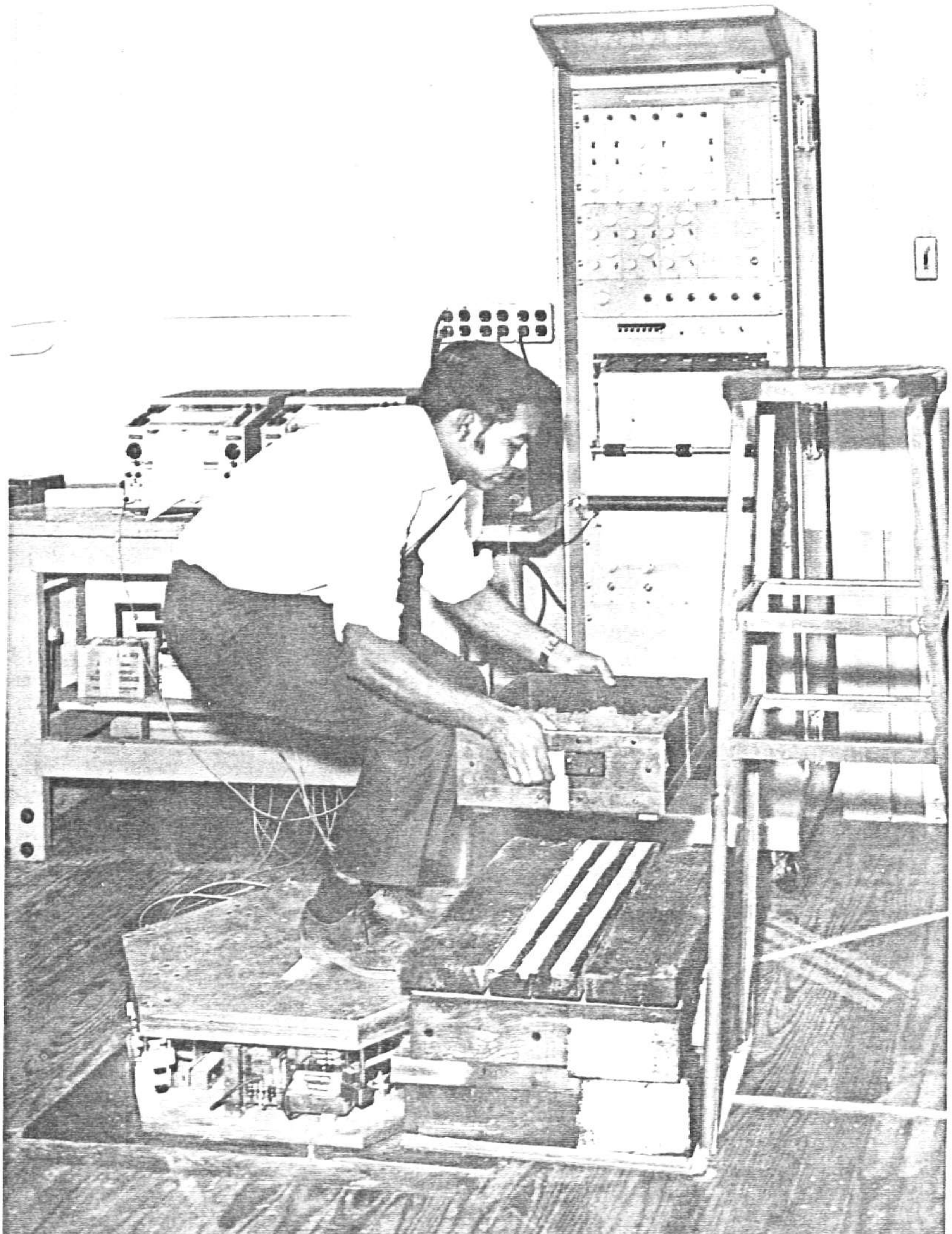
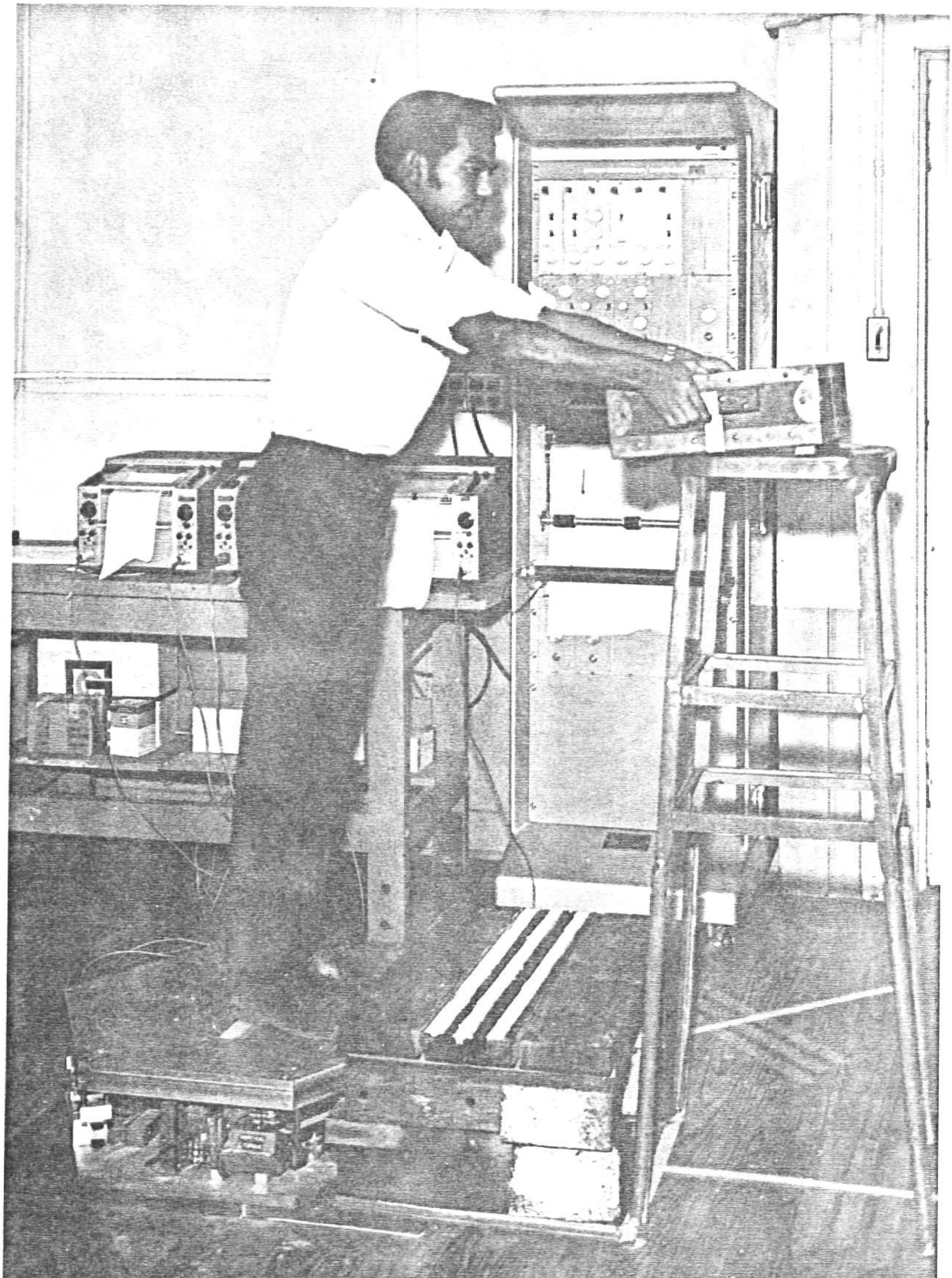


Figure 7. The end of lift and tote box being placed at 0 degrees.



degrees (Figure 9) depending on the condition. The box would then be taken from the shelf and then be replaced on the load platform by an assistant. The subject was also instructed to lift without a jerk. He was required to lift with an action that was smooth and steady so that there was as little impact as possible in order to minimize impact acceleration on the discs. The speed of "lift" was self-paced, as is generally the case in industrial lifting. Therefore, the subject worked according to his own "rhythm", such that he performed without strain or discomfort, weakened, overheated or out of breath.

The five subjects performed the tasks for the 15 conditions as listed in Table 1. The subjects repeated each lift four times at each condition, and rested standing ten seconds between lifts and three minutes lying down between conditions. The rest intervals were intended to counterbalance the effect of fatigue. All sessions began at least one hour after eating. One subject was run per day. Each subject completed the whole set of lifting over two days. On the first day, the subject performed the 15 lifting conditions (Replicate 1), and on the second day performed its replicate (Replicate 2), that is, the sequence of the conditions was reversed. For the individual subjects, these two days may have been successive days or over a period of ten days. The average of the trials of the first and second day was used as the criterion. The routine of the experiment has been designed to randomise all the variables as far as practicable. Table 3 shows the random sequence used.

Subjects.

Five male students from Kansas State University acted as subjects. Switzer (1962) demonstrated that stature affects weight lifting capacity. Subjects were chosen between 40-60 percentile (5' 8" - 5' 9½") of male heights

Figure 8. Tote box being placed at 90 degrees.

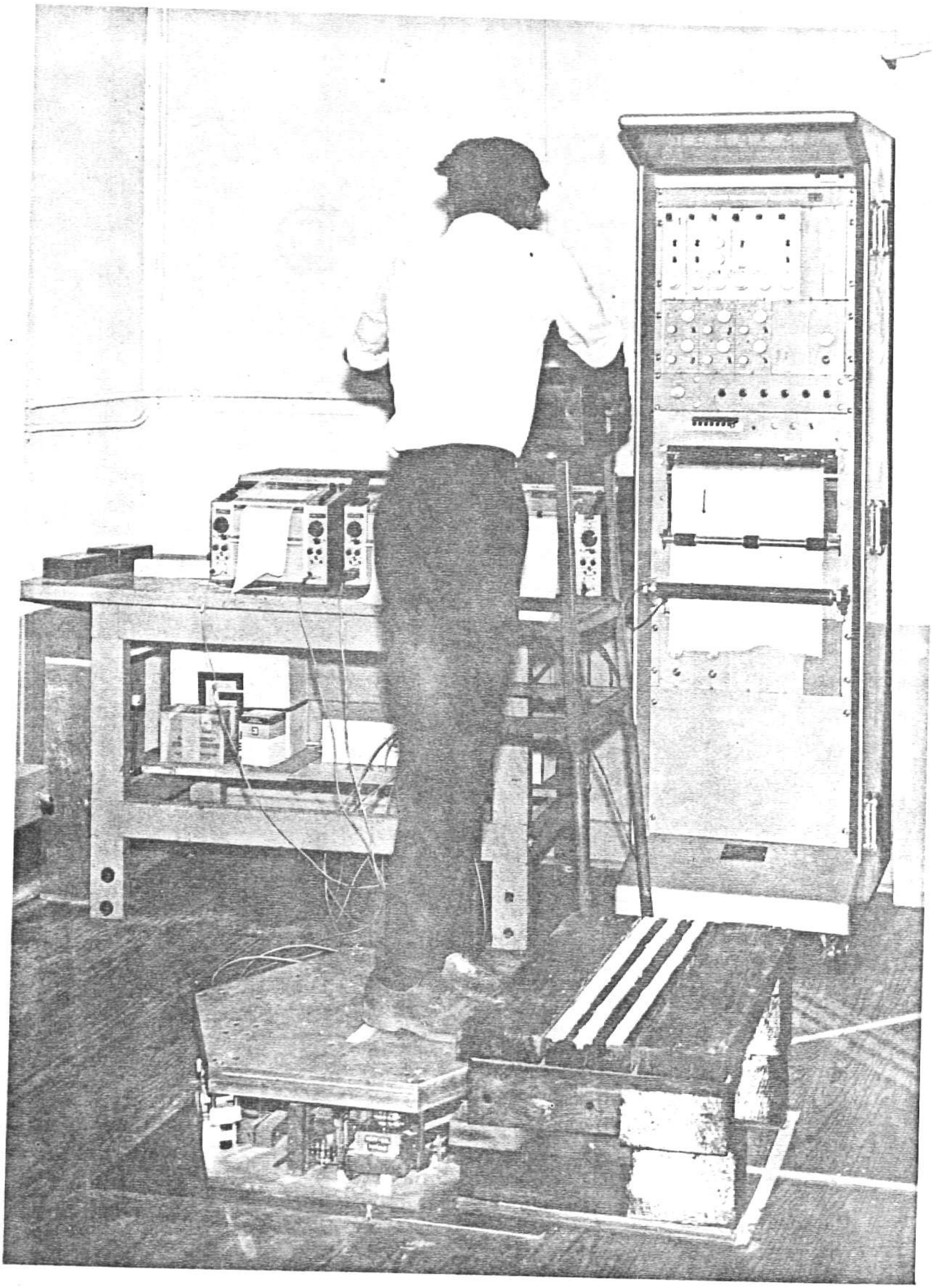


TABLE 3

Experimental Sequence of 1st Session for Subjects.

Subject	Condition														
1	15	8	4	3	9	13	2	7	5	11	12	14	1	6	10
2	14	12	13	1	9	3	15	5	2	6	11	4	7	8	10
3	9	14	10	5	2	11	7	6	8	13	12	15	1	4	3
4	13	5	14	7	9	12	11	1	8	4	15	3	6	10	2
5	12	11	4	9	6	10	14	1	7	13	15	2	8	5	3

in the United States. Subjects were chosen so that they satisfied the height condition and also had an average build besides being capable of lifting without injuring themselves. No student under 18 was chosen as a subject. All subjects were paid for their contribution by the hour.

RESULTS

After the experiment was completed, the output charts from the recorders were read. These readings in millimeters were converted into pounds and inch-pounds. These readings of forces and torques for every subject are listed in Table 4 through Table 9.

Lateral Force.

Replicate Effect. The replicate effect was studied by comparing the two replicates of lateral force for each subject, by means of a sign test. The result of the sign test (Table 10) showed that the difference between the two replicates was nonsignificant and they come from the same statistical population. This could also be interpreted as an absence of a significant learning effect over the two replicates.

Weight, Distance and Angle Effects. The 15 'conditions' of lift have been located on three orthogonal axes in the form of a cube as shown in Figure 6. The average for each of the 15 conditions and for each face of the cube has been shown in Table 11. For example, the average peak lateral force for condition one was 6.77 pounds and the average force for the plane ABCD was 4.84 pounds.

The effect of the change in parameters was calculated by taking the difference between each two opposite faces of the cube (Figure 5) and dividing it by the mean lateral peak force. The mean lateral peak force was 5.93 pounds.

Angle effect.

$$\text{Difference} = \text{Average of plane AGFD} - \text{Average of plane BCEH}$$

$$= |4.83 - 7.06|$$

$$= 2.23$$

TABLE 4

REPLICATES AND AVERAGES FOR LATERAL FORCE IN POUNDS

CONDITION	SUBJECT 4			SUBJECT 2			SUBJECT 1			SUBJECT 3			SUBJECT 5		
	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN
1	9.07	7.50	8.29	6.71	5.32	6.01	7.50	7.10	7.30	6.02	5.77	5.89	6.60	5.52	6.06
2	3.96	4.86	4.41	4.44	3.54	3.99	6.21	4.04	5.12	6.02	4.16	5.09	2.72	4.41	3.56
3	5.52	5.19	5.36	1.56	5.28	3.42	5.11	5.36	5.23	7.17	3.54	5.36	5.11	3.63	4.37
4	11.30	13.20	12.25	6.35	5.85	6.10	10.56	12.54	11.55	6.64	6.51	6.57	6.18	6.35	6.26
5	5.77	5.56	5.67	5.43	4.70	5.06	6.97	3.87	5.42	5.44	6.43	5.94	4.78	5.28	5.03
6	4.45	4.20	4.33	4.78	3.83	4.31	4.53	3.21	3.87	6.43	3.46	4.95	3.05	4.45	3.75
7	6.10	5.69	5.89	3.25	4.45	3.85	5.85	5.77	5.81	7.50	8.12	7.81	5.03	5.77	5.40
8	11.88	12.62	12.25	5.15	6.51	5.83	11.39	10.39	10.89	7.67	5.61	6.64	6.35	8.09	7.21
9	5.36	6.10	5.73	5.44	4.74	5.09	7.76	4.78	6.27	5.69	4.70	5.19	2.59	5.11	3.85
10	4.86	4.90	4.88	5.06	4.29	4.67	6.18	4.20	5.19	6.18	3.46	4.82	2.55	4.62	3.58
11	5.32	7.96	6.64	5.89	5.36	5.62	7.17	5.03	6.10	5.69	6.84	6.26	3.91	6.39	5.15
12	10.23	7.76	8.99	5.77	5.44	5.61	8.95	9.40	9.17	6.18	7.67	6.92	6.35	5.77	6.06
13	6.39	6.93	6.66	6.16	5.69	5.92	8.25	5.44	6.84	5.36	6.39	5.87	5.03	5.94	5.48
14	5.44	4.20	4.82	4.81	5.23	5.02	5.56	3.30	4.43	5.94	5.69	5.81	3.42	4.53	3.97
15	8.74	8.41	8.58	3.91	6.27	5.09	9.94	8.16	9.05	6.43	4.45	5.44	5.28	5.36	5.32

'ABLE 5

:EPLICATES AND AVERAGES FOR VERTICAL FORCE IN POUNDS

:CNDITICN	SUBJECT 4			SUBJECT 2			SUBJECT 1			SUBJECT 3			SUBJECT 5		
	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN
1	68.00	55.44	61.68	36.00	30.96	33.44	58.96	36.48	47.68	63.44	60.96	62.16	58.96	48.00	53.44
2	65.44	56.00	60.72	27.44	24.96	26.16	39.44	38.96	39.20	71.44	64.48	67.92	35.44	44.96	40.16
3	58.48	43.44	50.96	18.96	32.00	25.44	43.44	55.44	49.44	72.00	56.00	64.00	40.96	34.00	37.44
4	73.44	73.44	73.44	44.00	36.96	40.48	42.96	48.48	45.68	59.44	70.00	64.72	56.96	60.00	58.48
5	70.00	64.96	67.44	36.48	47.44	41.92	38.96	56.96	47.92	56.96	62.96	59.92	48.96	50.96	49.92
6	60.96	48.48	54.72	22.00	28.00	24.96	45.44	48.96	47.20	70.96	62.96	66.96	40.96	42.00	41.44
7	56.00	59.44	57.68	28.00	28.00	28.00	31.36	38.96	35.12	56.96	58.96	57.92	36.96	40.96	38.96
8	60.00	76.96	68.48	36.96	36.00	36.48	54.96	54.00	54.48	66.48	78.00	72.24	32.00	58.00	44.96
9	70.48	62.00	66.24	43.44	36.96	40.16	50.96	46.00	48.48	60.48	76.48	68.48	48.96	54.96	51.92
10	70.00	74.00	72.00	26.96	30.00	28.48	54.00	50.00	52.00	73.44	60.96	67.20	46.00	50.96	48.48
11	60.48	63.44	62.32	35.44	30.48	32.96	40.96	38.48	39.68	64.00	72.96	68.48	44.96	50.00	47.44
12	80.00	63.44	71.68	30.00	36.48	33.20	41.44	42.48	41.92	58.00	71.44	64.72	28.00	52.00	40.00
13	76.00	73.44	74.72	30.00	33.44	31.68	49.44	51.44	50.40	34.96	66.00	50.48	41.44	52.00	46.72
14	75.44	64.48	69.92	33.44	32.00	32.72	39.44	34.96	37.20	68.96	58.96	63.92	40.00	47.44	43.6[illegible]
15	78.00	62.00	70.00	36.00	40.00	38.00	46.48	48.00	47.20	62.96	64.96	63.92	32.96	56.00	44.48

TABLE 6

REPLICATES AND AVERAGES FOR FRONTAL FORCE IN POUNDS

CONDITION	SUBJECT 4 R1	SUBJECT 4 R2	SUBJECT 4 MEAN	SUBJECT 2 R1	SUBJECT 2 R2	SUBJECT 2 MEAN
1	24.00	19.24	21.62	15.74	14.74	15.24
2	21.24	15.12	18.18	20.74	18.00	19.36
3	18.62	17.74	18.18	11.74	11.50	11.62
4	11.74	13.00	12.36	10.50	11.86	11.18
5	22.24	22.24	22.24	26.24	27.00	26.62
6	21.74	23.12	22.42	21.50	13.24	17.36
7	21.50	18.00	19.74	11.00	9.50	10.24
8	14.62	17.74	16.18	16.50	10.62	13.56
9	20.00	22.00	26.00	24.74	23.24	23.98
10	24.50	24.36	24.42	21.74	19.50	20.62
11	17.74	17.00	17.36	13.36	12.00	12.68
12	16.36	13.62	14.98	7.50	9.24	8.36
13	24.74	15.36	20.04	13.12	14.36	13.74
14	21.24	13.24	17.24	11.00	13.86	12.42
15	21.36	16.00	18.68	21.00	16.00	18.50

CONDITION	SUBJECT 1 R1	SUBJECT 1 R2	SUBJECT 1 MEAN	SUBJECT 3 R1	SUBJECT 3 R2	SUBJECT 3 MEAN
1	21.00	27.00	24.00	17.50	17.24	17.36
2	18.50	22.74	20.62	21.74	19.74	20.74
3	12.62	24.50	18.56	16.24	14.74	15.48
4	21.66	26.50	24.08	14.24	18.00	16.12
5	32.74	31.50	32.12	19.00	24.24	21.62
6	19.62	22.00	20.80	14.12	22.24	18.18
7	9.36	16.00	12.68	13.50	13.00	13.24
8	10.24	19.00	14.62	15.74	22.50	19.12
9	34.24	26.10	30.16	16.00	30.00	23.00
10	26.12	35.00	30.56	17.00	27.00	22.00
11	13.74	19.50	16.62	15.00	15.74	15.36
12	12.12	15.50	13.80	13.00	11.24	12.12
13	24.74	23.74	24.24	9.36	16.12	12.74
14	15.24	18.50	16.86	12.82	12.74	12.78
15	16.36	25.74	21.04	15.24	20.24	17.74

CONDITION	SUBJECT 5 R1	SUBJECT 5 R2	SUBJECT 5 MEAN
1	10.00	13.00	11.50
2	10.50	14.50	12.50
3	8.74	11.74	10.24
4	17.50	8.00	12.74
5	13.00	19.00	16.00
6	19.00	13.50	16.24
7	9.50	9.74	9.6[illegible]
8	9.24	15.24	12.24
9	12.74	15.50	14.12
10	23.26	14.24	18.74
11	13.50	9.74	11.6[illegible]
12	9.00	9.00	9.00
13	11.74	12.24	11.98
14	8.12	12.74	10.18
15	14.50	11.30	13.00

TABLE 7

REPLICATES AND AVERAGES FOR SOMERSAULT TORQUE IN INCH POUNDS

CONDITION	SUBJECT 4			SUBJECT 2			SUBJECT 1			SUBJECT 3			SUBJECT 5		
	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN
1	544.50	462.00	502.92	643.50	506.88	574.86	960.96	961.62	960.96	547.96	561.50	554.40	891.00	452.42	671.88
2	416.46	433.62	425.04	552.42	511.50	531.96	849.42	800.38	825.00	627.00	577.50	601.92	705.54	495.00	599.94
3	540.54	445.50	493.02	445.50	532.62	502.26	825.00	981.42	902.88	907.50	478.50	693.00	852.92	772.00	812.46
4	668.58	945.12	808.50	826.96	685.08	757.02	990.00	1261.92	1125.96	973.50	627.00	799.32	1221.00	718.08	969.54
5	778.80	712.80	745.80	803.88	804.54	803.82	1125.96	1359.60	1242.78	865.92	615.12	740.52	981.42	817.08	898.92
6	490.38	569.58	529.98	412.50	284.46	348.48	627.00	726.00	676.50	655.38	474.54	564.96	462.00	462.00	462.00
7	384.12	498.96	441.54	440.88	744.48	592.68	656.04	874.50	764.94	528.66	436.05	492.36	469.92	561.00	515.46
8	445.50	684.42	564.96	668.58	594.00	630.96	751.08	849.42	799.92	507.54	442.46	475.00	861.96	503.59	682.44
9	573.54	524.04	548.46	639.54	557.04	597.96	957.00	1014.42	985.38	759.00	511.50	634.92	847.42	524.04	686.40
10	495.00	693.00	594.00	630.96	540.54	585.42	1097.58	1002.54	1050.06	701.58	544.50	623.04	775.50	536.58	656.04
11	412.50	766.92	589.38	704.88	536.58	620.40	894.96	1114.08	1004.52	684.42	714.12	698.94	997.92	586.08	792.00
12	597.96	601.92	599.94	651.42	445.50	548.46	964.92	973.50	968.88	511.50	441.54	476.52	808.50	487.05	647.46
13	503.58	453.42	478.50	528.00	445.50	486.42	891.00	1023.00	957.00	498.96	503.58	300.94	607.92	260.04	463.98
14	504.90	499.62	502.26	540.54	396.00	467.94	882.42	1039.50	960.96	726.00	457.36	591.36	478.50	453.42	465.96
15	614.46	573.54	594.00	709.50	685.08	696.96	1023.00	1270.50	1146.42	788.04	553.08	670.56	990.00	594.00	792.00

TABLE 8

REPLICATES AND AVERAGES FOR TWIST TORQUE IN INCH POUNDS

CONDITION	SUBJECT 4			SUBJECT 2			SUBJECT 1			SUBJECT 3			SUBJECT 5		
	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN
1	281.16	220.32	250.56	238.32	132.48	185.40	177.48	184.32	180.72	148.32	198.00	173.16	184.32	261.00	222.4[illegible]
2	49.32	76.32	62.64	63.00	65.88	644.40	58.32	69.48	63.72	49.32	61.20	55.08	117.00	45.00	81.00
3	270.00	186.48	228.24	126.00	175.32	150.48	159.48	171.00	165.24	164.16	243.00	203.40	164.16	229.32	196.56
4	256.32	216.00	236.16	290.16	209.16	249.48	229.32	220.32	224.64	241.20	265.32	253.08	180.00	306.00	243.00
5	60.48	54.00	57.24	67.32	54.00	60.48	72.00	90.00	81.00	42.48	112.32	77.40	117.00	76.32	96.4[illegible]
6	60.48	74.16	67.32	65.16	42.48	53.64	31.32	76.32	53.64	74.16	74.16	74.16	31.32	54.00	42.4[illegible]
7	207.00	218.16	212.40	81.00	157.32	119.16	177.48	189.00	183.24	112.32	279.00	195.48	150.48	182.16	166.32
8	213.48	243.00	228.24	274.32	285.48	279.72	225.00	216.00	220.32	119.16	256.32	187.56	162.00	299.16	230.40
9	76.32	76.32	76.32	78.48	40.32	59.40	78.48	81.00	79.56	87.48	126.00	106.56	121.32	126.00	123.4[illegible]
10	85.32	74.16	79.56	81.00	36.00	58.32	69.48	76.32	72.72	65.16	65.16	65.16	99.00	81.00	90.00
11	249.48	234.00	241.56	285.48	76.32	180.72	146.16	139.32	142.56	168.48	207.00	187.56	166.32	243.00	204.4[illegible]
12	218.16	265.32	241.56	222.48	103.32	162.72	195.48	202.32	198.72	123.48	265.32	194.40	148.32	292.32	220.3[illegible]
13	261.00	211.32	236.16	202.32	153.00	177.48	171.00	198.00	184.32	171.00	180.00	175.32	135.00	243.00	189.00
14	216.00	177.48	196.56	135.00	128.16	131.40	112.32	121.32	116.64	180.00	166.32	173.16	148.32	157.32	152.64
15	254.16	285.48	269.64	234.00	218.16	226.08	180.00	195.48	187.56	157.32	180.00	168.48	126.00	315.00	220.3[illegible]

TABLE 9

REPLICATES AND AVERAGES FOR CARTWHEEL TORQUES IN INCH POUNDS

CONDITION	SUBJECT 4			SUBJECT 2			SUBJECT 1			SUBJECT 3			SUBJECT 5		
	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN	R1	R2	MEAN
1	708.60	652.20	680.40	547.20	547.20	547.20	412.20	382.20	397.20	622.20	675.00	648.60	648.60	652.20	650.40
2	150.00	157.20	153.60	262.20	195.00	228.60	153.60	232.20	192.60	232.20	168.60	200.40	160.80	120.00	140.40
3	630.00	555.00	592.20	513.60	555.00	534.00	270.00	412.20	340.80	630.00	630.00	630.00	475.80	510.00	492.60
4	727.20	532.20	629.40	565.80	637.20	601.20	465.00	405.00	435.00	675.00	615.00	645.00	663.60	675.00	669.00
5	138.60	168.60	153.60	220.80	228.60	224.40	300.00	225.00	262.20	337.20	225.00	280.60	165.00	202.20	183.60
6	105.00	202.20	153.60	183.00	183.00	183.00	175.80	142.20	159.00	385.80	112.20	249.00	195.00	150.00	172.20
7	562.20	603.60	582.60	562.20	487.20	524.40	333.60	322.20	327.60	405.00	528.60	466.80	528.60	600.00	564.00
8	565.80	622.20	594.00	615.00	540.00	577.20	430.80	390.00	410.40	670.80	787.20	729.00	675.00	667.20	670.80
9	243.60	243.60	243.60	135.00	330.00	232.20	172.20	210.00	190.80	370.80	225.00	297.60	250.80	258.60	254.40
10	138.00	172.20	154.80	232.20	232.20	232.20	198.60	165.00	181.80	217.20	145.80	181.20	145.80	180.00	167.60
11	655.80	510.00	582.60	453.60	645.00	549.00	363.60	322.20	342.60	637.20	847.20	742.20	540.00	633.60	586.80
12	528.60	540.00	534.00	547.20	715.80	631.20	405.00	393.60	399.00	715.80	660.00	687.60	475.80	663.60	569.40
13	600.00	667.20	633.60	510.00	655.80	582.60	277.20	363.60	320.40	622.20	577.20	599.40	442.20	615.00	528.60
14	637.20	540.00	588.60	517.20	600.00	558.60	243.60	307.20	275.40	607.20	505.80	556.20	562.20	678.60	620.40
15	562.20	727.20	644.40	600.00	547.20	573.60	370.80	322.20	346.20	675.00	750.00	712.20	405.00	697.20	550.80

TABLE 10

Results of Sign Test ($\alpha = .05$) for Replicate Effect.

	Number of Pairs Compared	Number of Differences	Critical Number of Differences	Conclusion
Lateral	75	30	28	Non significant
Vertical	75	30	28	" "
Frontal	73 *	35	25	" "
Cartwheel	70 *	31	26	" "
Twist	74 *	27	27	" "
Somersault	73 *	27	25	" "

* For the frontal force, the actual number of pairs compared were 75, since there was a tie in two pairs, the number of pairs compared was reduced to 73. The same reasoning is applied for the 70, 74 and 73 pairs compared for cartwheel, twist and somersault, respectively.

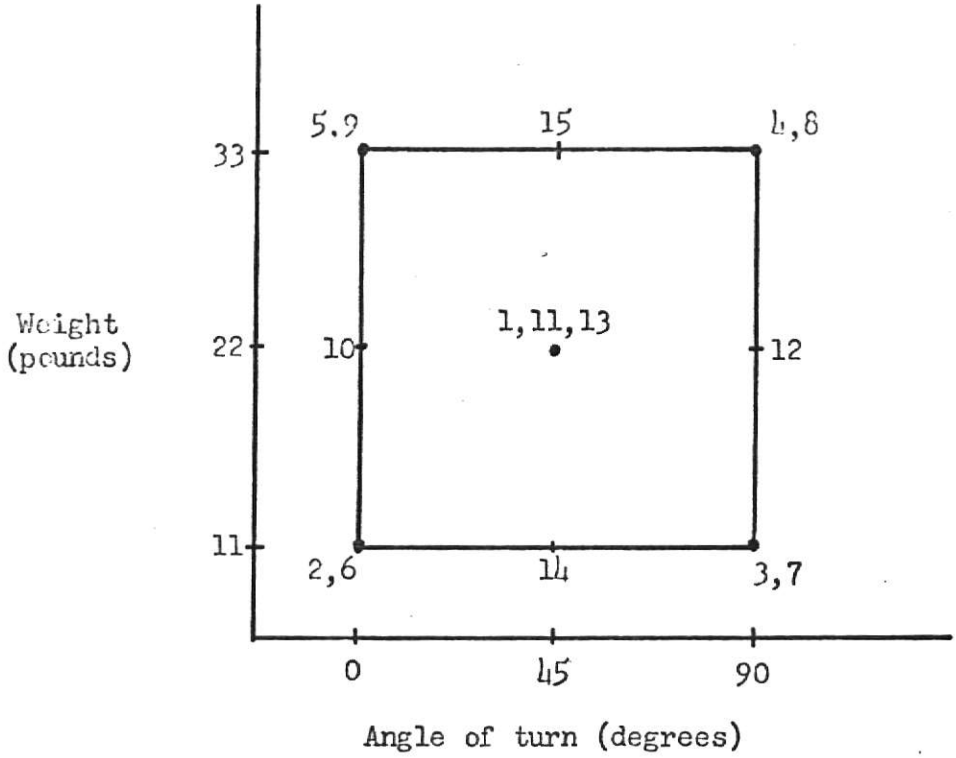


Figure 9. Experimental conditions analysed at various levels of weight and angle of turn (with distance axis collapsed).

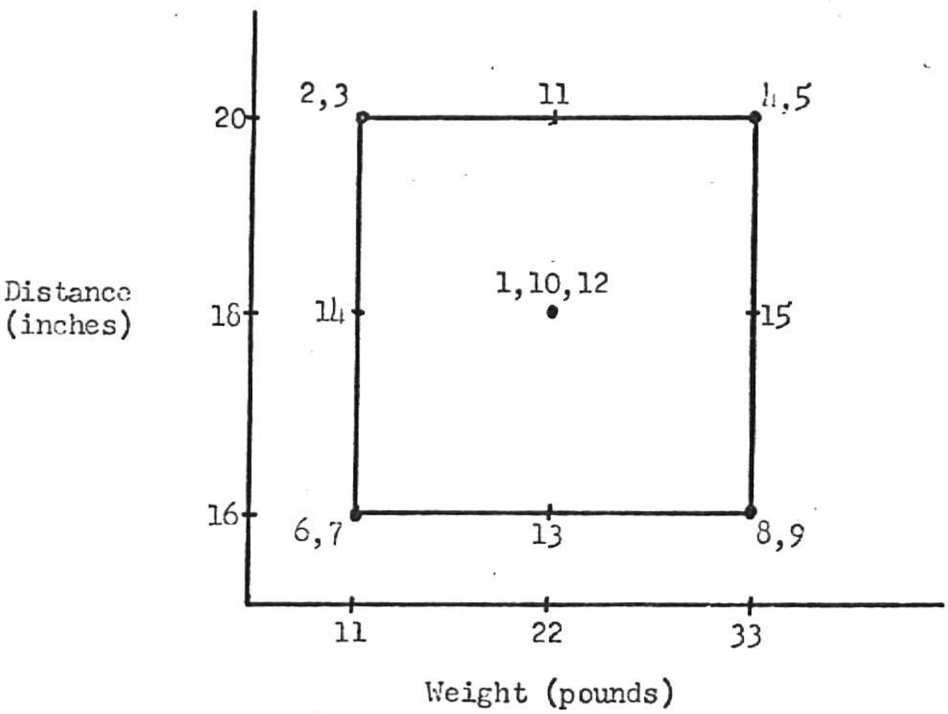


Figure 10. Experimental conditions analysed at various levels of distance and weight (with angle axis collapsed).

TABLE 11
AVERAGE FORCES (POUNDS) AND TORQUES (INCH POUNDS) FOR ALL CONDITIONS AND FACES ON THE CUBE

CONDITION	LATERAL	VERTICAL	FRONTAL	CARTWHEEL	SOMERSAULT	TWIST
1	6.77	51.68	17.94	584.76	653.00	202.46
2	4.47	46.83	18.28	183.12	596.76	65.36
3	4.79	45.45	14.81	517.92	678.08	188.78
4	8.63	56.56	15.29	595.92	892.12	241.27
5	5.47	53.42	23.75	220.92	886.38	74.52
6	4.28	47.05	19.00	163.36	516.38	58.24
7	5.81	43.53	13.10	493.08	561.39	175.32
8	8.65	55.32	15.14	596.28	634.65	229.24
9	5.27	55.76	23.45	243.72	690.62	59.64
10	4.67	53.63	23.26	182.52	701.71	73.15
11	6.01	50.09	14.72	560.64	741.04	191.37
12	7.42	50.10	11.65	564.24	653.65	203.54
13	6.21	50.80	16.54	532.92	577.36	345.91
14	4.85	49.48	13.89	519.84	597.69	154.08
15	6.76	52.72	17.79	565.44	779.98	214.41
ABCD	4.84	46.46	15.81	379.46	550.00	128.35
BCEH	7.06	50.19	13.99	553.48	683.99	207.63
EFGH	6.95	54.75	19.08	444.45	776.76	169.70
ADFG	4.83	51.33	21.54	202.72	673.37	72.06
ABGH	5.87	50.47	17.37	415.70	758.88	152.26
CDEF	6.04	50.49	17.44	409.87	596.08	179.55

Therefore, change in angle effect from 0 degrees to 90 degrees

$$= 2.23/5.93 \times 100$$

$$= 37.6 \text{ percent}$$

Weight effect.

Difference = Average of plane ABCD - Average of plane EFGH

$$= |4.84 - 6.95|$$

$$= 2.11$$

Therefore, change in weight effect from 11 pounds to 33 pounds

$$= \frac{2.11}{5.93} \times 100$$

$$= 35.6 \text{ percent}$$

Distance effect.

Difference = Average of plane AGHB - Average of plane CDEF

$$= |6.04 - 5.87|$$

$$= .17 \text{ percent}$$

Therefore, change in distance effect from 16 inches to 20 inches

$$= \frac{.17}{5.93} \times 100$$

$$= 2.8 \text{ percent}$$

Thus, changing the angle from 0 degree to 90 degrees changed the force by 38 percent, changing the weight from 11 pounds to 33 pounds changed the force by 36 percent and changing the distance from 16 inches to 20 inches changed the force by only 3 percent. These figures indicate that the distance effect was very small and therefore negligible as compared to those of weight and angle. Since the distance effect was negligible, the analysis of lateral force was reduced to the two variables of weight and angle of turn as shown in Figure 9. It was now possible to have several estimates of certain points. For example, 0 degrees and 11 pounds could be estimated from conditions two and six. In the following analysis, the means were used if more than one estimate was available.

An analysis of variance (Table 12) showed that the main effects of subject, angle and weight were significant ($\alpha = .05$) as well as all interactions.

Next, a series of sign tests were performed on each factor - level by level (Table 13). The fifteen pairs (five subjects at three levels of angle) indicated that the 0 degree (mean = 4.80 pounds) and the 45 degree forces were significantly different from the 90 degree forces (mean = 7.11 pounds). Thus, the mean force at 0 degrees is less than at 45 degrees and 45 degrees is less than 90 degrees. Similarly, the weight effect was also checked (Table 14). It was found that the 11 pounds (mean = 4.84 pounds) forces were significantly different from the 22 pounds (mean = 6.14 pounds) forces and 33 pounds (mean = 6.92) forces. However, the difference in forces between the 22 and 33 pounds of load was not statistically significant. Thus the force required for 11 pounds was significantly different than for those of 22 pounds and 33 pounds of load.

Vertical Force.

Replicate Effect. The replicate effect was studied by comparing the two replicates of vertical force for each subject, by means of a sign test. The results of the sign test (Table 10) showed that the difference between the two replicates were nonsignificant. It was concluded that there was no significant learning effect.

TABLE 12

ANALYSIS OF VARIANCE FOR LATERAL FORCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F RATIO	CRITICAL-F (ALPHA=.05)	DECISION
ANGLE	2	35.25	17.6	11.0	F(2,8) =4.4	SIGNIFICANT
WEIGHT	2	39.90	19.9	9.9	F(2,8) =4.4	SIGNIFICANT
SUBJECT	4	35.67	8.9	22.2	F(4,16)=3.0	SIGNIFICANT
ANGLE X WEIGHT	4	11.50	2.8	7.0	F(4,16)=3.0	SIGNIFICANT
ANGLE X SUBJECT	8	13.26	1.6	4.0	F(8,16)=2.5	SIGNIFICANT
WEIGHT X SUBJECT	8	16.36	2.0	5.0	F(8,16)=2.5	SIGNIFICANT
ERROR	15	7.12	.4			
TOTAL	44	159.06				

TABLE 13

AVERAGE VALUES BY SUBJECTS OF LATERAL FORCE WITH RESPECT TO DEGREES OF TURN.

	0 DEGREES	45 DEGREES	90 DEGREES
SUBJECT 1	5.90 *	9.14	11.33
SUBJECT 2	5.12	5.14	5.92
SUBJECT 3	5.62	5.50	6.67
SUBJECT 4	5.75	8.67	12.37
SUBJECT 5	4.48	5.37	6.80
SUBJECT 1	5.24 **	6.81	9.27
SUBJECT 2	4.72	5.91	5.66
SUBJECT 3	4.87	6.06	6.99
SUBJECT 4	4.93	7.27	9.08
SUBJECT 5	3.62	5.62	6.12
SUBJECT 1	4.54 ***	4.47	5.57
SUBJECT 2	4.18	5.07	3.67
SUBJECT 3	5.07	5.87	6.65
SUBJECT 4	4.41	4.87	5.68
SUBJECT 5	3.69	4.01	4.93
MEAN	4.80	5.98	7.11

* OBTAINED BY AVERAGING OVER CONDITION 5 AND 9.

** OBTAINED FROM CONDITION 10

*** OBTAINED BY AVERAGING OVER CONDITION 2 AND 6.

TABLE 14

AVERAGE VALUES OF LATERAL FORCES WITH RESPECT TO DIFFERENT LOADS.

	11 POUNDS	22 POUNDS	33 POUNDS
SUBJECT 1	5.57 *	9.27	11.33
SUBJECT 2	3.67	5.66	6.02
SUBJECT 3	6.65	6.99	6.67
SUBJECT 4	5.68	9.08	12.37
SUBJECT 5	4.93	6.12	6.80
SUBJECT 1	4.47 **	6.31	9.14
SUBJECT 2	5.07	5.91	5.14
SUBJECT 3	5.87	6.06	5.50
SUBJECT 4	4.87	7.27	8.67
SUBJECT 5	4.01	5.62	5.37
SUBJECT 1	4.54 ***	5.24	5.90
SUBJECT 2	4.18	4.72	5.12
SUBJECT 3	5.07	4.87	5.62
SUBJECT 4	4.41	4.93	5.75
SUBJECT 5	3.69	3.62	4.48
MEAN	4.84	6.14	6.92

* OBTAINED BY AVERAGING OVER CONDITION 3 AND 7.

** OBTAINED BY AVERAGING OVER CONDITION 14.

*** OBTAINED BY AVERAGING OVER CONDITION 2 AND 5.

<u>Weight, Distance and Angle Effects.</u> The average for each of the fifteen conditions and for each face of the cube corresponding to the vertical force has been shown in Table 11.

The effect of the change in parameters was determined by the same method as used earlier. The mean vertical peak force was 50·60 pounds.

Angle effect.

Difference = Average of plane AGFD - Average of plane BCEH

$= |51.33 - 50.10|$

$= 1.14$

Therefore, change in angle effect from 0 degrees to 90 degrees

$= \frac{1.14}{50.60} \times 100$

$= 2.2$ percent

Weight effect.

Difference = Average of plane ABCD - Average of plane EFGH

$= |46.46 - 54.75|$

$= 8.29$

Therefore, change in weight effect from 11 pounds to 33 pounds

$= \frac{8.29}{50.60} \times 100$

$= 16.4$ percent

Distance effect.

Difference = Average of plane AGHB - Average of plane CDEF

$= |50.49 - 50.47|$

$= .02$

Therefore, the change in distance effect from 16 inches to 20 inches

$$= \frac{.02}{50.60} \times 100$$

$$= .04 \text{ percent}$$

Thus, changing the angle from 0 degrees to 90 degrees changed the force by 2.2 percent, changing the weight from 11 pounds to 33 pounds changed the force by 16.4 percent and changing the distance from 16 inches to 20 inches changed the force by only .04 percent. Therefore, a change in weight has the greatest effect. The effect of changing the distance and the angle has very negligible effect compared to the weight. Therefore, distance and angle were neglected thus reducing the analysis of vertical force to one variable of weight only.

An analysis of variance (Table 15) showed that the subject and weight effects were significant ($\alpha = .05$). All other effects and the corresponding interactions were significant. Therefore, as far as the vertical force is concerned, besides the subject variation, it is the weight of the load that is of primary importance.

Since the effect of the distance and angle was negligible for the vertical force, a sign test was applied to check the weight effect (Table 16). It was found that between the 11 pound forces (mean = 46.97 pounds) and the 22 pound forces (mean = 51.53 pounds) there was no significant ($\alpha = .05$) difference. Similarly, there was no significant difference between the 22 pound forces and 33 pound forces (mean = 54.30 pounds). Significant difference was present between the 11 pound forces and the 33 pound forces.

TABLE 15

ANALYSIS OF VARIANCE FOR VERTICAL FORCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F RATIO	CRITICAL-F (ALPHA=.05)	DECISION
SUBJECT	4	7375.14	1843.78	94.1	F(4,16)=3.01	SIGNIFICANT
WEIGHT	2	406.39	203.19	23.8	F(2,8) =4.46	SIGNIFICANT
ANGLE	2	14.59	7.79	.7	F(2,8) =4.46	NON SIGNIFICANT
SUBJECT X ANGLE	8	85.90	10.73	.5	F(8,16)=2.59	NON SIGNIFICANT
SUBJECT X WEIGHT	8	68.25	8.53	.4	F(8,16)=2.59	NON SIGNIFICANT
ANGLE X WEIGHT	4	108.38	27.09	1.3	F(4,16)=3.01	NON SIGNIFICANT
ERROR	16	313.48	19.59			
TOTAL	44	8372.12				

TABLE 16

AVERAGE VALUES OF VERTICAL FORCES WITH RESPECT TO DIFFERENT LOADS.

	11 POUNDS	22 POUNDS	33 POUNDS
SUBJECT 1	42.28	41.92	50.08
SUBJECT 2	26.72	32.20	38.48
SUBJECT 3	60.96	64.72	68.48
SUBJECT 4	54.32	71.68	70.96
SUBJECT 5	38.20	40.00	51.72
SUBJECT 1	37.20	45.92	47.20
SUBJECT 2	32.72	32.69	38.00
SUBJECT 3	63.92	60.37	63.92
SUBJECT 4	69.92	66.10	70.00
SUBJECT 5	43.68	49.20	44.48
SUBJECT 1	43.20	52.00	48.20
SUBJECT 2	25.56	28.48	41.04
SUBJECT 3	67.44	67.20	64.20
SUBJECT 4	57.72	72.00	66.84
SUBJECT 5	40.80	48.48	50.92
MEAN	49.67	51.53	54.20

Frontal Force.

Replicate Effect. The replicate effect was studied by comparing the two replicates of frontal force for each subject, by means of a sign test. The result of the sign test (Table 10) showed that the difference between the two replicates were nonsignificant ($\alpha = .05$).

Weight, Distance and Angle Effects. The average for each of the fifteen conditions and for each face of the cube corresponding to the vertical force has been shown in Table 11.

The effect of the change in parameters was determined by the same procedure shown earlier. The mean frontal peak force was 17.53 pounds. The results have been given below.

Change in angle effect from 0 degrees to 90 degrees

$$= \frac{7.55}{17.53} \times 100$$

$$= 43 \text{ percent}$$

Change in weight effect from 11 pounds to 33 pounds

$$= \frac{3.27}{17.53} \times 100$$

$$= 18.65 \text{ percent}$$

Change in distance effect from 16 inches to 20 inches

$$= \frac{.07}{17.53} \times 100$$

$$= .4 \text{ percent}$$

By studying the magnitude of the effects, it is quite evident that the change in angle has the most severe effect on the frontal force. The change in distance effect is .4 percent which is very small compared to the change in angle effect of 43 percent and the change in weight effect of 18.65 percent. Since the distance effect was neglected, the analysis of the frontal force was reduced to two variables of weight and angle of turn as shown in Figure 9.

An analysis of variance for the frontal force (Table 16b) showed all main effects of subjects, weight and angle to be significant ($\alpha = .05$). The angle x weight and subject x weight interactions were also significant. Hence, for the frontal force, besides the effect of subject variation, the angle and weight are significantly important variables and there is also an internal relationship between the angle and weight.

From the sign tests performed on each factor - level by level (Table 17), it was found that the 0 degree forces (mean = 21.83 pounds) was significantly different than the 45 degree forces (mean = 16.03 pounds) and the 45 degree force was significantly different than the 90 degree forces (mean = 13.64 pounds). It could also be concluded that the mean force at 0 degrees is more than at 45 degrees and 45 degrees is more than 90 degrees. The weight effect was similarly checked (Table 18). It was found that the 11 pound forces (mean = 15.49 pounds) and the 22 pound forces (mean = 17.10 pounds) were not significantly different, also the difference between the 22 pound forces and the 33 pound forces (mean = 19.69) were not significantly different. But the 11 pound forces and the 33 pound forces were significantly different, the mean for the 33 pound load was larger than that of the 11 pound load.

<u>Somersault Torque.</u>

<u>Replicate Effect.</u> The sign test was made on the two replicates. The results of the sign test (Table 10) showed that there was no significant difference between the two replicates and therefore it was possible to conclude the absence of learning effect.

TABLE 15b

ANALYSIS OF VARIANCE FOR FRONTAL FORCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F RATIO	CRITICAL-F (ALPHA=.05)	DECISION
SUBJECT	4	381.35	95.33	42.2	F(4,16)=3.01	SIGNIFICANT
ANGLE	2	535.42	267.70	46.2	F(2,8) =4.46	SIGNIFICANT
WEIGHT	2	85.10	42.50	7.1	F(2,8) =4.46	SIGNIFICANT
SUBJECT X ANGLE	8	45.57	5.69	2.5	F(8,16)=2.59	NON SIGNIFICANT
SUBJECT X WEIGHT	8	47.34	5.91	2.6	F(8,16)=2.59	SIGNIFICANT
ANGLE X WEIGHT	4	63.27	15.81	7.0	F(4,16)=3.01	SIGNIFICANT
ERROR	16	36.17	2.26			
TOTAL	44	1194.22				

TABLE 17

AVERAGE VALUES OF FRONTAL FORCES WITH RESPECT TO DIFFERENT ANGLES OF TURN.

	DEGREES		
	0	45	90
SUBJECT 1	31.14	21.04	19.35
SUBJECT 2	25.30	18.50	12.37
SUBJECT 3	22.31	17.74	17.62
SUBJECT 4	24.12	18.68	14.27
SUBJECT 5	15.06	13.00	12.49
SUBJECT 1	30.56	21.62	13.80
SUBJECT 2	20.62	13.88	8.36
SUBJECT 3	22.00	15.15	12.12
SUBJECT 4	24.42	19.67	14.98
SUBJECT 5	18.74	11.70	9.00
SUBJECT 1	20.71	16.86	15.62
SUBJECT 2	18.36	12.42	10.93
SUBJECT 3	19.46	12.78	14.36
SUBJECT 4	20.30	17.24	18.96
SUBJECT 5	14.37	10.18	9.93
MEAN	21.83	16.03	13.64

TABLE 18

AVERAGE VALUES OF FRONTAL FORCES WITH RESPECT TO DIFFERENT LOADS.

	11 POUNDS	22 POUNDS	33 POUNDS
SUBJECT 1	15.62	13.80	19.35
SUBJECT 2	10.93	8.36	12.37
SUBJECT 3	14.36	12.12	17.62
SUBJECT 4	18.96	14.98	14.27
SUBJECT 5	9.93	9.00	24.98
SUBJECT 1	16.86	21.62	21.04
SUBJECT 2	12.42	13.88	18.50
SUBJECT 3	12.78	15.15	17.74
SUBJECT 4	17.24	19.67	18.68
SUBJECT 5	10.18	11.70	13.00
SUBJECT 1	20.71	30.56	31.14
SUBJECT 2	18.36	20.62	25.30
SUBJECT 3	19.46	22.00	22.31
SUBJECT 4	20.30	24.42	24.12
SUBJECT 5	14.37	18.74	15.06
MEAN	15.49	17.10	19.69

Weight, Distance and Angle Effects. The average for each of the 15 conditions and for each face of the cube corresponding to the vertical force has been shown in Table 11.

The effect of the change in parameter was determined by the same procedure as done for earlier cases. The mean peak somersault torque was 680.68 inch-pounds.

Change in angle effect from 0 degrees to 90 degrees

$$= \frac{5.62}{680.68} \times 100$$

$$= .735 \text{ percent}$$

Change in weight effect from 11 pounds to 33 pounds

$$= \frac{186.76}{680.68} \times 100$$

$$= 27.5 \text{ percent}$$

Change in distance effect from 16 inches to 20 inches

$$= \frac{162.80}{680.68} \times 100$$

$$= 23.8 \text{ percent}$$

The maximum effect occurred for the change in weight from 11 pounds to 33 pounds; however in this case the least effect of .735 percent was caused by the change of body turn from 0 degrees to 90 degrees, and comparatively the effect of body turn for the somersault could therefore be neglected. In other words, the somersault torque remains essentially constant irrespective of the body turn. Therefore, the analysis of the somersault torque reduced to two variables of distance and weight as shown in Figure 10.

The analysis of variance for the somersault torque (Table 19) showed the weight, distance and subject effects to be significant. No interaction was significant.

TABLE 19

ANALYSIS OF VARIANCE FOR SOMERSAULT TORQUE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F RATIO	CRITICAL-F (ALPHA=.05)	DECISION
SUBJECT	4	1016791.74	254197.9	84.1	F(4,16)=3.0	SIGNIFICANT
WEIGHT	2	267831.21	133915.6	31.9	F(2,8) =4.4	SIGNIFICANT
DISTANCE	2	199683.02	99841.5	17.8	F(2,8) =4.4	SIGNIFICANT
SUBJECT X DISTANCE	8	44829.20	5603.6	1.8	F(8,16)=2.5	NON SIGNIFICANT
SUBJECT X WEIGHT	8	33533.56	4191.6	1.3	F(8,16)=2.5	NON SIGNIFICANT
DISTANCE X WEIGHT	4	21270.32	5317.5	1.7	F(4,16)=3.0	NON SIGNIFICANT
ERROR	16	48348.96	3021.8			
TOTAL	44	1632288.01				

From the sign tests performed on each factor - level by level (Table 20), it was found that the somersault torques for the 11 pounds of load (mean = 591.33 inch-pounds) and the 22 pounds of load (mean = 662.02 inch-pounds) were not significantly different. However, the torque for the 33 pound load (mean = 777.30) was (= .05) significantly different from the torques for the 11 pounds and 22 pounds of load. The distance effect was similarly checked by means of a sign test (Table 21). The results showed that the torque for the 16 inch distance (mean = 592.96 inch-pounds) was significantly different than the torque for the 18 inch distance (mean = 681.78 inch-pounds), and the 20 inch distance torque (mean = 755.92 inch-pounds) was significantly different than the 18 inch distance torque.

Cartwheel Torque.

Replicate Effect. The replicate effect was studied by applying a sign test. The result of the sign test (Table 10) showed that there was no significant difference (= .05) between the two replicates.

Weight, Distance and Angle Effects. The average for each of the fifteen conditions and for each face of the cube corresponding to the vertical force has been shown in Table 11.

The effect of the change in parameter was determined by the same procedure shown earlier. The mean peak cartwheel torque was 400.94 inch-pounds. The results have been given below.

Change in angle effect from 0 degrees to 90 degrees

$$= \frac{350.76}{400.94} \times 100$$

$$= 87.7 \text{ percent}$$

TABLE 20

AVERAGE VALUES BY SUBJECTS OF SOMERSAULT TORQUES WITH RESPECT TO DIFFERENT LOADS.

	11 POUNDS	22 POUNDS	33 POUNDS
SUBJECT 1	720.72	957.00	892.65
SUBJECT 2	470.58	486.42	614.46
SUBJECT 3	528.66	500.94	554.96
SUBJECT 4	485.76	478.50	556.71
SUBJECT 5	488.73	463.98	624.42
SUBJECT 1	960.96	993.30	1146.42
SUBJECT 2	467.94	569.58	696.96
SUBJECT 3	591.36	551.32	670.56
SUBJECT 4	502.26	565.62	594.00
SUBJECT 5	465.96	658.46	792.00
SUBJECT 1	863.94	1004.52	1184.37
SUBJECT 2	510.51	620.40	730.45
SUBJECT 3	647.46	698.94	770.22
SUBJECT 4	459.03	539.38	777.15
SUBJECT 5	706.20	792.00	934.23
MEAN	591.33	662.00	777.30

TABLE 21

AVERAGE VALUES BY SUBJECTS OF SOMERSAULT TORQUES WITH RESPECT TO DIFFERENT DISTANCES.

	16 INCHES	18 INCHES	20 INCHES
SUBJECT 1	892.62	1146.42	1184.37
SUBJECT 2	614.46	696.96	780.45
SUBJECT 3	564.96	670.56	770.22
SUBJECT 4	556.71	594.00	777.15
SUBJECT 5	684.42	792.00	934.23
SUBJECT 1	957.00	993.30	1004.52
SUBJECT 2	486.42	569.58	620.40
SUBJECT 3	500.94	551.32	698.94
SUBJECT 4	478.50	565.62	589.38
SUBJECT 5	463.98	658.46	792.00
SUBJECT 1	720.72	960.96	863.94
SUBJECT 2	470.58	467.94	510.51
SUBJECT 3	528.66	591.36	647.46
SUBJECT 4	485.76	502.26	459.03
SUBJECT 5	488.73	465.96	706.20
MEAN	592.96	681.78	755.92

Change in weight effect from 11 pounds to 33 pounds

$$= \frac{64.99}{400.94} \times 100$$

$$= 16.3 \text{ percent}$$

Change in distance effect from 16 inches to 20 inches

$$= \frac{5.87}{400.94} \times 100$$

$$= .147 \text{ percent}$$

Therefore, for the cartwheel torque, the change in angle or turn effect and the weight effect are very dominant, whereas the effect of distance is relatively negligible. Therefore, the analysis of the cartwheel torque was reduced to the two variables of weight and angle of turn as shown in Figure 9.

An analysis of variance for the cartwheel torque (Table 22) showed the angle and subject effects to be significant ($\alpha = .05$). The subject x angle interaction was also significant.

From the sign tests performed on each factor - level by level (Table 23), it was found that the torque at 0 degrees (mean = 199.36 inch-pounds) was significantly different than those for 45 degrees (mean = 548.24 inch-pounds) and 90 degrees (mean = 555.28). Also, there was no significant difference between the torque for 45 degrees and 90 degrees. A similar analysis in terms of weights showed (Table 24) that there was no significant difference between the 11 pound (mean = 403.06 inch-pounds) torque and the 22 pound (mean = 435.40 inch-pounds) torque. Also there was no significant difference between the 22 pound torque and the 33 pound (mean = 457.35 inch-pounds) torque. However, the mean cartwheel torque at 33 pounds was much larger than for 11 pounds.

TABLE 22

ANALYSIS OF VARIANCE FOR CARTWHEEL TORQUE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F RATIO	CRITICAL-F (ALPHA=.05)	DECISION
ANGLE	2	1242229.31	621114.6	46.0	F(2,8) = 4.46	SIGNIFICANT
WEIGHT	2	28634.79	14317.3	1.2	F(2,8) = 4.46	NON SIGNIFICANT
SUBJECT	4	215425.91	53856.4	39.5	F(4,16)= 3.01	SIGNIFICANT
SUBJECT X ANGLE	8	107659.25	13457.4	9.0	F(8,16)= 2.59	SIGNIFICANT
SUBJECT X WEIGHT	8	11137.07	1392.1	1.01	F(8,16)= 2.59	NON SIGNIFICANT
ANGLE X WEIGHT	4	6776.43	1694.1	1.24	F(4,16)= 3.01	NON SIGNIFICANT
ERROR	16	21828.73	1364.3			
TOTAL	44	1633691.49				

TABLE 23

AVERAGE VALUES OF CARTWHEEL TORQUES WITH RESPECT TO DIFFERENT ANGLES OF TURN.

	0 DEGREES	45 DEGREES	90 DEGREES
SUBJECT 1	226.50	346.20	422.70
SUBJECT 2	228.30	573.60	589.20
SUBJECT 3	289.20	712.20	687.00
SUBJECT 4	198.60	644.40	611.70
SUBJECT 5	219.00	550.80	669.90
SUBJECT 1	181.80	353.40	399.00
SUBJECT 2	232.20	559.60	631.20
SUBJECT 3	181.20	663.40	687.60
SUBJECT 4	154.80	632.20	534.00
SUBJECT 5	162.60	588.60	569.40
SUBJECT 1	175.80	275.40	334.20
SUBJECT 2	205.80	558.60	529.20
SUBJECT 3	224.70	556.20	548.40
SUBJECT 4	153.60	588.60	587.40
SUBJECT 5	156.30	620.40	528.30
MEAN	199.36	548.24	555.28

TABLE 24

AVERAGE VALUES BY SUBJECTS OF CARTWHEEL TORQUES WITH RESPECT TO DIFFERENT LOADS.

	11 POUNDS	22 POUNDS	33 POUNDS
SUBJECT 1	334.20	399.00	422.70
SUBJECT 2	529.20	631.20	589.20
SUBJECT 3	548.40	687.60	687.00
SUBJECT 4	587.40	534.00	611.70
SUBJECT 5	528.30	569.40	669.90
SUBJECT 1	275.40	353.40	346.20
SUBJECT 2	558.60	559.60	573.60
SUBJECT 3	556.20	663.40	712.20
SUBJECT 4	588.60	632.20	644.40
SUBJECT 5	620.40	588.60	550.80
SUBJECT 1	175.80	181.80	226.50
SUBJECT 2	205.80	232.20	228.30
SUBJECT 3	224.70	181.20	289.20
SUBJECT 4	153.60	154.80	198.60
SUBJECT 5	156.30	162.60	109.98
MEAN	403.06	435.40	457.35

Twist Torque.

Replicate Effect. The result of the sign test made on the two replicates showed that there was no significant difference between the two replicates and it was concluded that there was no significant learning effect.

Weight, Distance and Angle Effects. The average for each of the 15 conditions and for each face of the cube corresponding to the turn torque has been shown in Table 11.

The effect of the change in parameters was determined in the same procedure as done for earlier cases. The mean peak turn torque was 151.60 inch-pounds.

Change in angle effect from 0 degrees to 90 degrees

$$= \frac{135.57}{151.60} \times 100$$

$$= 89.4 \text{ percent}$$

Change in weight effect from 11 pounds to 33 pounds

$$= \frac{41.35}{151.60} \times 100$$

$$= 27.3 \text{ percent}$$

Change in distance effect from 16 inches to 20 inches

$$= \frac{27.19}{151.60} \times 100$$

$$= 17.9 \text{ percent}$$

The magnitude of the three effects were large and unlike the other cases no parameter was neglected. Therefore, for the analysis of turn torque all the three parameters are important and the situation has been represented by a cube as shown in Figure 5. In this case, it was not possible to have several estimates of one point.

The sign test was performed on each factor. However, it was only possible to compare the opposite walls of the cube since no middle plane was available.

Tables 25, 26, and 27 show the values of averages in terms of different parameters for the different conditions on the walls of the cube. It was found that there was no significant difference between the twist torques for 16 inches (mean = 137.97 inch-pounds) and the turn torques for 20 inches (mean = 142.98 inch-pounds). With respect to the weight, there was a significant difference between the twist torque for 11 pound load (mean = 121.93 inch-pounds) and the 33 pound load (mean = 158.52 inch-pounds). Similarly, with respect to the angle, the twist torque for the 0 degrees was significantly different (mean = 71.79 inch-pounds) than the 90 degrees twist torque (mean = 208.65 inch-pounds). Therefore, the mean torque when facing straight and not involving a body turn is less than the mean torque when the body is turned through 90 degrees.

The analysis of variance test (Table 28) showed that all main effects and their interactions, excepting those of angle x subject and angle x distance x subject interactions, were concluded nonsignificant.

TABLE 25

AVERAGE VALUES BY SUBJECTS OF TWIST TORQUES WITH RESPECT TO DIFFERENT DISTANCES.

	16 INCHES	20 INCHES
SUBJECT 1	53.64 *	63.72
SUBJECT 2	53.64	64.40
SUBJECT 3	74.16	55.08
SUBJECT 4	67.32	62.64
SUBJECT 5	42.48	81.00
SUBJECT 1	183.24	165.24
SUBJECT 2	119.16	150.48
SUBJECT 3	195.48	203.40
SUBJECT 4	212.40	228.24
SUBJECT 5	166.32	196.56
SUBJECT 1	79.56	81.00
SUBJECT 2	59.40	60.48
SUBJECT 3	106.56	77.40
SUBJECT 4	76.32	57.24
SUBJECT 5	123.48	96.48
SUBJECT 1	220.32	224.64
SUBJECT 2	279.72	249.48
SUBJECT 3	187.56	253.08
SUBJECT 4	228.24	236.16
SUBJECT 5	230.40	243.00
MEAN	137.97	142.48

* OBTAINED FROM CONDITION 6.

TABLE 26

AVERAGE VALUES BY SUBJECTS OF TWIST TORQUES WITH RESPECT TO DIFFERENT LOADS.

	11 POUNDS	33 POUNDS
SUBJECT 1	63.72 *	81.00 **
SUBJECT 2	64.40	60.48
SUBJECT 3	55.08	77.40
SUBJECT 4	62.64	57.24
SUBJECT 5	81.00	96.48
SUBJECT 1	165.24	224.64
SUBJECT 2	150.48	249.48
SUBJECT 3	203.40	253.08
SUBJECT 4	228.24	236.16
SUBJECT 5	196.56	243.00
SUBJECT 1	53.64	79.56
SUBJECT 2	53.64	59.40
SUBJECT 3	74.16	106.56
SUBJECT 4	67.32	76.32
SUBJECT 5	42.48	123.48
SUBJECT 1	183.24	220.32
SUBJECT 2	119.16	279.72
SUBJECT 3	195.48	157.56
SUBJECT 4	212.40	228.24
SUBJECT 5	166.32	230.40
MEAN	121.93	158.52

* OBTAINED FROM CONDITION 2.
** OBTAINED FROM CONDITION 5.

TABLE 27

AVERAGE VALUES BY SUBJECTS OF TWIST TORQUES WITH RESPECT TO DIFFERENT ANGLES OF TURN.

	0 DEGREES	90 DEGREES
SUBJECT 1	81.00 *	224.64 **
SUBJECT 2	60.48	249.48
SUBJECT 3	77.40	253.08
SUBJECT 4	57.24	236.16
SUBJECT 5	96.48	243.00
SUBJECT 1	79.56	220.32
SUBJECT 2	59.40	279.72
SUBJECT 3	106.56	187.56
SUBJECT 4	76.32	228.24
SUBJECT 5	123.48	230.40
SUBJECT 1	53.64	183.24
SUBJECT 2	53.64	119.16
SUBJECT 3	74.16	195.48
SUBJECT 4	67.32	212.40
SUBJECT 5	42.48	166.32
SUBJECT 1	63.72	165.24
SUBJECT 2	64.40	150.48
SUBJECT 3	55.08	203.40
SUBJECT 4	62.64	228.24
SUBJECT 5	81.00	196.56
MEAN	71.79	208.65

* OBTAINED FROM CONDITION 5.
** OBTAINED FROM CONDITION 4.

TABLE 28

ANALYSIS OF VARIANCE FOR TWIST TORQUE.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F RATIO	CRITICAL-F (ALPHA=.05)	DECISION
WEIGHT	69331.62	1	69331.62	2.10	F(1,4) = 7.71	NON SIGNIFICANT
ANGLE	63703.26	1	63703.26	.37	F(1,4) = 7.71	NON SIGNIFICANT
DISTANCE	17811.52	1	17811.52	.48	F(1,4) = 7.71	NON SIGNIFICANT
SUBJECT	207814.50	4	51953.62	.94	F(4,40)= 2.61	NON SIGNIFICANT
WEIGHT X ANGLE	68438.93	1	68438.93	.51	F(1,4) = 7.71	NON SIGNIFICANT
WEIGHT X DISTANCE	21968.42	1	21968.42	.66	F(1,4) = 7.71	NON SIGNIFICANT
WEIGHT X SUBJECT	110649.56	4	27662.39	.50	F(4,40)= 2.61	NON SIGNIFICANT
ANGLE X DISTANCE	1100.37	1	1100.37	.007	F(1,4) = 7.71	NON SIGNIFICANT
ANGLE X SUBJECT	640903.00	4	160225.75	2.89	F(4,40)= 2.61	SIGNIFICANT
DISTANCE X SUBJECT	146406.00	4	36601.50	.66	F(4,40)= 2.61	NON SIGNIFICANT
WEIGHT X DISTANCE X SUBJECT	131808.93	4	32952.23	.59	F(4,40)= 2.61	NON SIGNIFICANT
WEIGHT X ANGLE X DISTANCE	12105.56	1	12105.56	.21	F(1,4) = 7.71	NON SIGNIFICANT
WEIGHT X ANGLE X SUBJECT	528787.25	4	132196.81	2.39	F(4,40)= 2.61	NON SIGNIFICANT
ANGLE X DISTANCE X SUBJECT	587767.00	4	146941.75	2.65	F(4,40)= 2.61	SIGNIFICANT
ANGLE X DISTANCE X SUBJECT X WEIGHT	136333.50	4	34083.37	.61	F(4,40)= 2.61	NON SIGNIFICANT
ERROR	2210397.99	40	55259.94			
TOTAL	4955332.41	79				

DISCUSSION

In order to evaluate the implications of the experimental results, a few important points will be discussed in this section. Consideration will be given to the statistical analysis made on the variables studied and will be followed by specific comments made concerning each phase of the findings associated with the characteristics of this experiment.

Studying carefully the output as measured by the force platform, it was noticed for some cases that for the same task the forces and torques among subjects were not very much alike, instead there were large differences. For example, in the somersault torque (Table 7), for condition three, the values for subject one for replicate one and two are 540.54 and 445.50, respectively, whereas subject four had 907.50 and 478.50 for replicate one and two, respectively. Such differences could be attributed either to the possibility that the recorder was picking up "static" from the surroundings or because of individual differences. From the analysis of variance for each of the forces and torques excepting the twist torque, subject variation was found to be significant suggesting the latter explanation. In spite of the fact that subjects were asked to avoid jerky movements, there were cases where light jerky movements were present. Since the jerky motions record more peak forces and torques, these differences in motions could be responsible for subject variability. Differences in body size as reflected in anthropometric measurements, especially the length of the leg and arm might affect the force applied. The way a subject shifted his weight on the various parts of the body, while lifting, may have caused some differences in the forces and torques. Since this study is the first of its kind because of its specific objectives and because of the restricted ranges along with the fact that there is the presence of individual differences, no generalizations can be made at this stage.

The fact that there were no replicate effects has been supported by statistical tests. The absence of replicate effect can also be seen if Table 4 to Table 9 are closely studied. For example, in the lateral force (Table 4), for condition three, subject one has 5.52 and 5.19 pounds for replicate one and two, respectively, which shows replicate one and two were very close.

A summary table (Table 29) has been made which gives the mean forces and torques for the major experimental parameters. As can be observed, the vertical forces were much larger than the frontal and lateral forces. Such a finding seems reasonable since for a lifting task it should be the vertical component of force that should be most dominant. The lateral forces were the smallest of the three forces. This would suggest that whatever the lifting job may be, whether it involves any body turn or not, it should be the vertical force that must get a greater consideration and it may be the vertical force that will determine the limiting conditions. For the three torques, on the average the somersault torques are the largest and the twist torques are the smallest. However, though the relative magnitude of the twist torque is the lowest, still it is not known whether a torque of such magnitude on the spine is harmful or not.

As would be expected, for the ranges studied in this experiment, the effect of weight for all the forces and torques was consistently strong and significant. Therefore, for any model of lifting, weight should be the primary variable for all the three forces and three torques. Considering the vertical force, it was only the weight that had any considerable effect, the effect of angle of turn and the distance of the load (for the range studied)

TABLE 29

MEANS OF FORCES AND TORQUES FOR THE THREE LEVELS OF EACH VARIABLE.

		VERTICAL (POUNDS)	FRONTAL (POUNDS)	LATERAL (POUNDS)	CARTWHEEL (INCH POUNDS)	SOMERSAULT (INCH POUNDS)	TWIST (INCH POUNDS)
	11	46.46	15.81	4.84	379.46	599.00	128.35
WEIGHT	22	51.28	16.82	6.22	485.02	665.35	253.28
(POUNDS)	33	54.75	19.08	6.95	444.45	770.76	169.75
	0	51.33	21.54	4.83	202.72	678.37	72.66
ANGLE	45	50.29	16.18	6.12	552.72	669.81	221.65
(DEGREES)	90	50.19	13.99	7.06	553.48	683.99	257.63
	16	50.49	17.44	6.04	409.87	596.08	179.55
DISTANCE	18	51.15	16.91	6.00	483.36	677.20	169.53
(INCHES)	20	50.47	17.37	5.87	415.70	758.88	152.36

was very small and negligible. Thus, for a vertical force acting through the center of the spine, it would be the magnitude of that force only that would matter in determining the safe limits. Since the force is balanced and also since distance and angle of turn (resulting in torque) are insignificant, the stresses and strains to which the spine is subjected are reduced to a minimum. It is for this reason that the subjects were instructed to keep their backs as straight as possible while lifting. This indirectly reflects the reasoning behind Jonock's (1964) conclusion that the most efficient way of transporting heavy objects is by balancing them on the head, since stresses and strains on the spine are reduced to minimum under such loading. Since the findings of the present study have shown that along the vertical direction, the magnitude of the centrally balanced load is all that matters and that the effects of distance and angle (resulting to torques) are negligible, it suggests that the vertical force is not a threat as far as torques are concerned and therefore heavy vertical loads could be lifted (within limits) provided proper lifting techniques are used. The upper limit for such loads could be found by more experimental studies.

The present study has also showed subject variability. This suggests that for the same lifting conditions, one subject could experience a greater stress than the other. Therefore, methods must be devised to determine the stress and find out under what conditions and for what anthropometric measurements the stresses become critical. This calls for more research where subjects should be selected with different arm lengths, leg lengths or height and more lifting tasks should be designed with larger ranges of parameters. Once the limitations are found then, accordingly the appropriate man should be selected for the job and then proper training in lifting should be given to him. Training in lifting is essential, as this could reduce back injuries, reduce lost time and increase efficiency. With heavier loads, workers tend to to shift from lifting with the legs to lifting with the back. Therefore, heavy loads should always be used for training, and periodic checking is necessary to detect shifts to back lifting. The lateral and frontal forces show a common pattern of behavior. For both these forces, angle and weight effects were strong, whereas an increase in distance within the range studied did not have an appreciable change in the forces. The change in the lateral and frontal forces for an increase of distance from 16 inches to 20 inches was three percent and five percent, respectively.

For the cartwheel torque, the effect of two variables of angle and weight were also very strong. As the angle of turn increased, the mean peak torque increased sharply between 0 degrees (200 inch-pounds) and 45 degrees (550 inch-pounds). However, there was no appreciable increase in mean peak torque from 45 degrees to 90 degrees. Therefore, the stress on the spinal column increases rapidly between 0 and 45 degrees. At this stage, the sudden high increase of torque from 0 to 45 degrees and a low increase from 45 to 90 degrees is unexplainable. But it could be concluded that if a job involved a lift with 45 degrees turn and another with 90 degrees turn, the cartwheel torque would not be dangerously different and larger at 90 degrees. Of course, it would be safer if there was no turn involved at all. The weight effects also show an increase of torque with the increase of weight. However, the increase in torque is not so sudden as in the case of turn.

For the somersault torque, both distance and weight were the stronger parameters. This is expected since the somersault effect created, largely depends on the distance of the weight from the spine and on the weight; therefore, the larger the weight and distance, the greater is the torque, regardless of the degrees of turn. From the analysis, it was concluded that the torque remained essentially constant with the increase in angle of turn. The increase in torque from 16 to 18 and 18 to 20 inches were gradual and fairly constant. The increase of torque from lifting a 11 pound load to a 22 pound load was not significant and therefore it would not make much difference in somersault torque whether a 11 pound load or a 22 pound load was being lifted, the stress conditions would not change significantly.

The twist torque was unique in nature. All the three variables of distance, weight and angle of turn were dominant. The most dominant of them being the angle of turn, the change in angle effects from 0 degrees (mean = 70 inch-pounds) to 90 degrees (mean = 200 inch-pounds) being 90 percent. Once again, it would be wiser not to design a job with such a large angle of turn. Though distance effect was conspicuous, but there was no significant difference in torques from 16 inches to 20 inches. In other words, as far as the twist torque is concerned, a job designed with a distance of 20 inches is as safe as a job with a distance of 16 inches under the same loading condition used in this study.

The effect of angle of turn was significant for cartwheel and twist torques. Also noted earlier, the distance effect was significant in some cases. This latter finding is in agreement with Ticheauer (1966) who demonstrated the importance of horizontal distance between the weight and spine. However, he did not analyse the effect of distance individually on each of the six forces and torques.

As for the magnitude of the forces and torques for each task obtained from the force platform, nothing can be concluded about whether the magnitudes were too high or low. There is no way of finding this out at the present stage. However, the subjects did not complain of fatigue or pain and so the author feels that the values of torques and forces were not high but within limits. Also, according to Woodson and Conover (1964), the heaviest load of 33 pounds for the type of lifting used in this study was well below the recommended limits (75 pounds).

Incorrect lifting, repeated lifting, loss of balance while lifting are frequently the reasons of accident and permanent back injury. Good movement makes the work easier and can prevent strain. The basic factors of lift are: correct placement of feet, keeping a straight back, bending the knees, assuring proper hold (palmar grip), and lifting with legs. Turning with the load should be accomplished with the feet. This study was not an optimization study on distances, weights and angles of turn. The aim was not to find the best distance or weight or angle for least stress; on the contrary, it was an investigation on the behavior of these three variables within a certain range of values. The author feels that this study could be and should be extended to a large scale experiment by choosing a wider range of values and having more levels in each variable.

CONCLUSIONS

The study undertaken in this thesis provides information for lifting tasks with respect to the three parameters of distance, weight and angle of turn in terms of all possible forces and torques.

1. Experimental results showed large individual differences.
2. Statistical tests concluded the absence of replicate effect.
3. For the vertical force, only weight was a significant contributor. Angle of turn and distance were not.
4. For the frontal force, lateral force and cartwheel torques, both the angle effect and the weight effect were important. Distance was negligible in all three cases.
5. For the somersault torque, weight and distance effects were equally important. The angle effect was negligible.
6. The twist torque showed all three parameters to be effective.
7. As would be expected and as it can also be observed, for the ranges studied in this experiment, the effect of weight for all the forces and torques was consistently strong and significant.
8. For the three forces, the distance effect was found negligible for the range of distances, weights and angles studied in this experiment. However, distance effect might become significant if a larger range of distance was studied.
9. The average cartwheel torque showed an extremely sharp rise from 0 degrees to 45 degrees. On the other hand, there was no appreciable increase from 45 degrees to 90 degrees. Therefore, if a job involved a lift with 45 degrees turn and another

job with a 90 degree turn, the cartwheel torque would not be dangerously different and larger at 90 degrees. However, it would be safer not to have any body turn at all.

10. The findings on the twist torque were also interesting. All three variables were concluded effective. The most dominant effect being the change in angle effect. Once again, it would be wiser not to design a job with such a large angle of turn.

The present study could have useful implications. In order to do this, an elaborate and exhaustive study of the parameters is essential. Since no previous studies with exactly the same aim have been done and since the present study is only exploratory, additional experimentation is recommended in this area.

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FORCES AND TORQUES INVOLVED IN LIFTING

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ABSTRACT

A force platform was used to study the behavior of three parameters, distance, weight and angle of turn for a typical lifting task. The distance of the weight from the spine was 16, 18 or 20 inches. The weights used were 11, 22 or 33 pounds. The angles of turn selected were 0, 45 or 90 degrees. For this study, fifteen combinations of these conditions were selected. Five male subjects performed the tasks four times and on two occasions.

It was concluded that for all the three forces (lateral, vertical and frontal) and the three torques (cartwheel, somersault and twist) there was no significant learning effect. For the lateral force, the change in weight and angle effect were 36 percent and 38 percent, respectively; the distance effect was negligible. The vertical force showed a change of 16.4 percent for an increase in weight from 11 pounds to 33 pounds. The frontal force showed a change of 43 percent from 0 degrees to 90 degrees and a change of 43 percent from 0 degrees to 90 degrees and a change of 16 percent from 11 pounds to 33 pounds. The effect of distance was negligible. For the twist torque, all the three variables had large effects. A change in angle from 0 degrees to 90 degrees caused a change of 89 percent, a change in weight from 11 pounds to 33 pounds caused a change of 27 percent and a change in distance from 16 to 20 inches caused a 17 percent change in this torque. The present study has various practical implications and further research and study is needed.