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Three-Dimensional Lifting Model For Non-Homogeneous Loads

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A 3-dimensional model and analysis methodology is suggested for treating lifting tasks when unbalanced loads are involved. The paper describes the biomechanical equations that are coupled with the worker's posture geometry, to address a practical problem of non-symmetric lifting. The analysis has a dominant biomechanical modeling scope, as it contains a breakdown of the internal lifting forces resulting from posture and external loads acting on the body. The load model represents the acting forces due to unbalanced lifting, which is commonly found in industrial situations. The suggested model allows the user to simulate the influence of the practical load distribution, aiding safe design of a lifting job.

manual lifting non-symmetric lifting biomechanics modeling posture analysis

1. INTRODUCTION

For many years, the act of lifting has been of great concern to those who are active in occupational safety, especially to industrial planners and preventive work medicine practitioners. It is a common reality that much of the industrial lifting involves lifting acts, where workers handle unstable loads due to content and loads that are non-symmetrical due to shape. These loads are generating counter balance body behavior acting to compensate the content or shape of the load, which results in a non-symmetrical lifting.

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Because manual lifting acts are performed frequently by many individuals, as a daily job requirement, it is only logical that some of those loads will lead to lifting injuries.

It has been stated by Chaffin and Page (1994) that if for some reason an object must be lifted in a twisted asymmetric posture, the 3 Dimensional Static Strength Prediction Program (3DSSPP) model predicts greater torso compression forces, which results in counter stress due to hip strength and balance acting forces. From observation, load lifting is incorporating different body postures by males and females. Body behavior will differ at the work site and at home, these will be used differently at performing tasks or at leisure activities, and so forth. To maintain appropriate health, the human musculoskeletal system is continuously performing counter balancing postures, which allows successful lifts for given loads. The spine at act, while serving also as a dynamic controller, is found to be an ultimate lifting mechanism that is very difficult to model, as discussed by Shoaf, Genaidy, Karwowski, Waters, and Christensen (1997).

It is relatively complicated to accurately model symmetrical lifting and it is even more complex when non-symmetrical loads are to be lifted. A fairly large number of studies are found in the literature, which contributes to the modeling of this wonder machine—most of them deal with manual materials handling in symmetrical lifting. The health care industry, especially nurses, as reported by Bewick and Gardner (2000), are famous to suffer from non-symmetrical lifting problems. Although a considerable amount of practical lifting is non-symmetrical, a fairly limited number of studies has been addressed to model unbalanced lifting.

Lifting of non-homogeneous loads is commonly found in industrial situations, where many individuals are required as part of the job to perform manual materials handling. Unbalanced lifting occurs when a load to be lifted is not homogeneous in its content, or the content is unstable (liquid), which changes its center of gravity while the weight is handled. There are no published figures on workers who experienced health trauma due the handling of unbalanced loads. It is estimated that the relative figures for lifting injuries with an unbalanced object will be considerabe.

The seriousness of the low back injury problem due to the lifting act is reflected in the related loss of working days and the growing number of occupational compensation claims. According to the World Health Organization (1995), back injury resulting from manual materials handling activities is the major source of lost time. This has been so reported over the last three decades. In the late 1970s, Snook (1978) reported that 79% of the manual materials handling injuries were to the low back. In the 1980s, Lahey (1984) and may others reported that back injuries alone cost an estimated US $14 bn a year. In the late 1980s, according to Ayoub and Mital (1989), the number of people suffering, or who have once suffered from low back pain in the USA in the 1980s increased by 7 m. In the late 1990s the trunk was the most affected body part for disabling work injuries in every industry division, in both the USA and Canada (Kumar, 2001).

Not only is the economic damage for the industrial enterprises enormous, but the physical consequences for the workers themselves could be severe and can result, for some, in permanent damage. Pope, Frymoyer, and Andersson (1984) presented figures showing that in the USA about 400,000 reported complaints of low back injuries with an average cost of US $4,000 per complaint. A study done in Israel by Gilad and Shani (1982) shows that the cost of back trauma is related exponentially according to injury severity. As an example, back injuries that resulted in work absenteeism of over 180 days represented 8% of the total injured population, whereas the cost in medical treatment, companies' losses, and insurance costs represented 50% of the overall back injury costs for the same period. In the USA 3–4% of the work force has compensated low back injury each year, and the cost of this exceeds US $28 bn. Such figures advocate that there is a growing need for prevention of such disorders from spreading among the working population.

Through biomechanics research history, many models have been developed and are constantly under research to cover a wide range of lifting acts (Kroemer, 1984). Lifting models range from two-dimensional static models to more complex three-dimensional dynamic models, such as the dynamic three-dimensional trunk model, which relates to low back disorders (Marras et al., 1993). The characteristics that are frequently accounted for by these models are the number of segments representing the human body in the plane or the space. Others are load size, human limitations as considered in the model, type of load—due to content, load size, external forces analysis, internal forces analysis at the low back level.

To reveal the relation between low back pain and lifting tasks, the Bureau of Labor Statistics (1999) exhibits numbers showing that lifting tasks are responsible for half of the low back injuries, whereas 10 to 20% of work accidents are caused by lifting tasks. In this paper on non-symmetrical lifting analysis, the authors hope to contribute to the general research of lifting, by presenting a model for the determination of the lifting act when non-homogeneous loads are to be handled. The approach in this model enables the user to evaluate lifting tasks in industrial situations, where load creates non-balanced forces on the musculoskeletal system. The model is able to analyze lifting stress due to the handling of an unbalanced and an odd-shaped load. This is to complement present two- and three-dimensional models, in which non-symmetrical lifts can not be evaluated adequately.

2. METHODOLOGY

The methodology presented in this study is based on the well-established approach to model the different reactions acting at the low back spine, at the L5/S1 intervertebral disk during lifting. When the body is bending over to reach the object and lift it, a load moment is created as a result of the weight lifted and the horizontal distance from weight to the disk. Back muscles consequently respond and create a counter moment around the spine axis. As a result, the intervertebral disk is subjected to compression forces perpendicular to the disk and shear forces parallel to the disk. The disk is subjected to permanent erosion during its life cycle because of the various activities a human performs, and in particularly the lifting activities, as discussed by Andersson, Chaffin, Herrin, and Matthew (1985). Low back pain is the general result of these activities on the deteriorated disks.

The following example can explain the enhanced potential damage to the L5/S1 disk during the lifting act: When a 20-kg box is lifted from the floor with the horizontal distance from the box to the disk being 40 cm, the compression force raises as much as 4,000 N. One can predict that when this load is non-homogeneous in content, or it is unbalanced, the resulting forces will exceed the mentioned value. On the other hand, while analyzing low back pain risks in meat processing plants, Das and Sengupta (2000) stated that occupational back injury is a major concern in the industry. They found that compressing forces at the L5/S1 disk, for a normal slump (25º), a severe bend (45º), and a very severe bend (70º) did not exceed 4,000 N. The computed L5/S1 forces did not exceed the safe limit of 3,400 N, commonly used for manual lifting tasks. This advocates for sheer forces due to unbalance body maneuvers during task execution. It is therefore why frequent load lifting activities that are required by a profession, have to be carefully monitored by a sort of simulation and designed to reduce potential hazards.

Ayoub stated in 1980 that a wide agreement exists between researchers that lifting activities have to be carefully designed to enhance safety (Ayoub, Mital, Asfour, & Bethea, 1980). Chaffin and Andersson (1999) refer to many others who advocate this statement. In the following three-dimensional lifting model, which is aimed at analysing non-symmetric lifting acts, one step further is proposed.

Our approach is that lifting task simulation models, these days they are called evaluation models, must be available to all key personnel who specialize in manual materials handling. These must provide reliable results in a minimum amount of time, when analyzing a task that is to take place in a factory or in any other work place. The parameters input in the model should accurately represent the task, the worker, and the surroundings. A computerized approach using a program named Lifter was developed at Technion Work Study Laboratory, Israel, along these very lines. This model for simulation and a biomechanics analysis of non-symmetrical lifting tasks introduces a friendly simulation of an existing lifting task on site. It includes

- a three-dimensional analysis,
- an analysis of postures recorded during the lifting act,
- a program that operates from a PC-based software package.

The model supports characteristics that have not been fully taken into account by previous models:

- a non-homogeneous load analysis,
- the practice of single- or two-handed lifting.

The Lifter program provides output figures designed to help the user to determine points of potential hazards during a lifting scenario. The program provides

- compression and shear forces acting on the low back at the L5/S1 disk,
- external forces and moments acting at the L5/S1 level,
- back and legs posture during a lift as segmental angles,
- National Institute for Occupational Health (NIOSH) limits and recommendations for the lift that is being analyzed.

The model is based on data obtained from the actual task as recorded at the work site with a standard video camera and a simple filming setup. Three still pictures are taken from the movie to represent the real postures of the specific lifting act. These postures are digitized and serve as postural input to the program. Although the model would support any three postures, it is recommended to relate and digitize one picture at the beginning of the lift, one half-way, and one at the end of the lifting act. This is to ensure a proper covering of the lift. The program assumes that the lift is performed in one continuous motion, so that all accelerations are small and therefore the initial forces of both the body elements and the lifted object are neglected.

The geometrical values of the digitized frames and external data such as load, anthropometry, task frequencies, and so forth, are fed into the program. The software calculates the forces and moments acting on the low back and presents the result on a graphic screen. A theoretical model was developed including the aforementioned features. It is composed of four sub-models interacting with the external world and among them. These are the load model, the three-dimensional body segment model, the low back model, and the NIOSH (1981) recommendations for lifting.

2.1. The Load Model

The purpose of this model is to establish a correlation between the weight distribution within the lifted load and the forces acting at the L5/S1 level. The model represents common loads of lifting found in industrial situations. It allows the user to simulate the influence of the practical load distribution, to the design of the job. The model assumes that manual lifted loads can be demonstrated in a rectangular box shape. The following parameters are used to define the load, total weight, geometrical sizes of the box (maximal box width will be body width), weight distribution within the box. The box, which represents the load, is then divided into two geometrical parts, the front part and the back part, with the back part being close to the body during the lift. Each of these parts is divided into 16 equally sized cubes. Each cube is defined as homogeneous in its content and has a known weight. Thus when assigning different segmental weights to the cubes through box volume, one can define the load to be lifted as non-homogeneous in its content. By assuming that every cube is homogeneous, we conclude that the center of mass of the cube is at its geometrical center. It is then trivial to calculate the location of the center of mass of a given load. The load parameters then are l—length; w—width; h—height; P—weight; $PW_{I,J}$—percentage of the weight in cube I, J; I = 1, 2; J = 1, 2, 3, ... ,16; F_L, F_R—the force applied by the load on the left and right hand; M_{Lt}, M_{Rt}—the moment applied by the load on the left and right hands around X, Y, and Z axes, (t = X, Y, Z).

We divide the load into two parts, G_R, G_L, as seen in Figure 1. The left side, G_L, will include cubes 1:1, 1:2, 1:5, 1:6, 1:9, 1:10, 1:13, 1:14, 2:1, 2:2, 2:5, 2:6, 2:9, 2:10, 2:13, 2:14. The right side, G_R, includes cubes 1:3, 1:4, 1:7, 1:8, 1:11, 1:12, 1:15, 1:16, 2:3, 2:4, 2:7, 2:8, 2:11, 2:12, 2:15, 2:16.

$F_L = P \bullet g \bullet PW_{I,J}$ for I and J in G_L

$F_R = P \bullet g \bullet PW_{I,J}$ for I and J in G_R (g = 9.81)

Moments at the hands can be calculated, because we know the location of the center of mass at each of the half-loads. Thus we can find the torque applied at each hand by assuming that load is grasped by both sides. The sub-model enables outputs of the forces and moments acting at each hand during the lift.

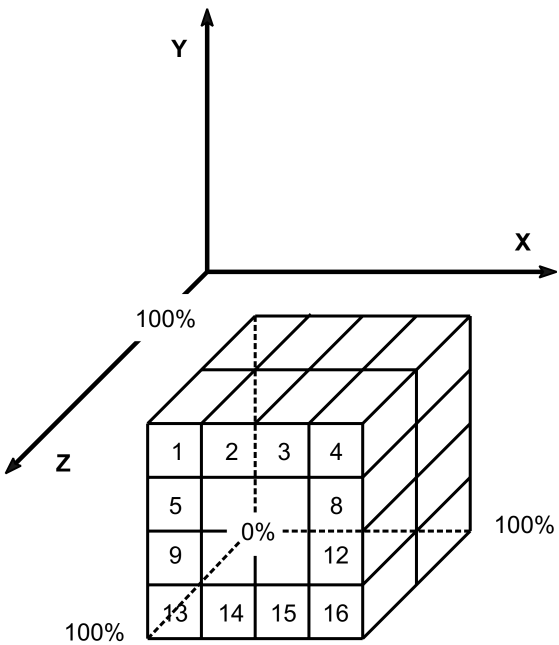


Figure 1. The theoretical lifting box with sub-properties and the relative orientation to the axis system.

2.2. The Three-Dimensional Body Segment Model

The model is made of 15 segments linked by 19 joints. It calculates the external forces acting on the lower lumbar joint, as seen in Figure 2. The mathematical equations are classical in manner and give consistent solutions, the equations are based on equilibrium between forces and moments. For each segment we provide its actual anthropometric characteristic, such as weight, length, location of the center of mass. These values are directly derived from the height, weight, gender, and age of a practical lifting worker, and from references such as the NASA (National Aeronautics and Space Agency) Anthropometric Source Book (NASA, 1978).

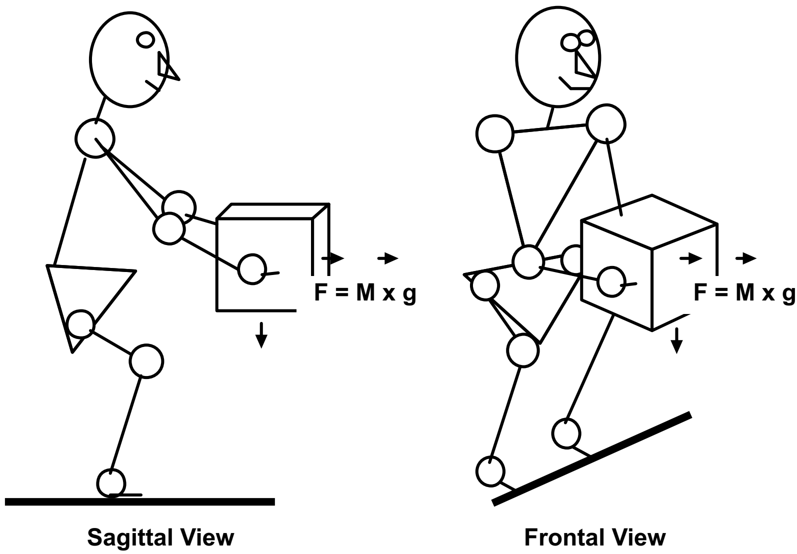


Figure 2. The Lifter body segment model and load.

For the purpose of this kind of simulation these values are fairly sufficient as the model intends to deal with risks involved in a certain population category composed from working individuals. We define the following parameters: W_L—weight of segment L, J_iCM_L—distance between joint J_i and segment L's center of mass, J_1–J_2—segment length between joints J_1 and J_2, F_J—force acting at joint J_i, M_J—moment acting at joint J_i, α_L—segment angle at the proximal joint with the X–Z plane.

For segment L, which is between joints J_1 and J_2 when J_1 is defined as a proximal joint, the angle α_L of the segment in the proximal joint relative to the X–Y plane,

$$J_1 = (X_1,\ Y_1,\ Z_1),$$
$$J_2 = (X_2,\ Y_2,\ Z_2),$$
$$\alpha_L = \mathrm{ArcTan}\ (Y_2 - Y_1) / \sqrt{(X_2 - X_1)^2 + (Z_2 - Z_1)^2}.$$

For each segment we develop the equilibrium equation. Because Lifter is a static model the force on the segments is due to the load and the weight of the segments, the force vector is directed downward, we can say,

$$M_{JY} = FJZ = FJX = 0.$$

From equilibrium equations, we obtain,

$$FJ_1Y = FJ_2Y + W_L \text{ for each joint } J_i,$$
$$MJ_1K = MJ_2K + J_1CM_L \bullet \cos\ \alpha_L \bullet W_L + (J_1 - J_2) \bullet \cos\ \alpha_L \bullet FJY_2, \qquad K = X, Z.$$

As the load sub-model calculated the forces and moments acting at the hands, we can calculate with the aforementioned equations the forces and moments at each joint. The purpose of using the sub-model is to get the external forces and moments acting at the L5/S1 level. Once we have this information, we feed it into the low back model in order to calculate the internal forces acting at the L5/S1 level.

2.3. The Low Back Model

We refer to the three-dimensional low back model introduced by Schultz and Andersson (1981), which takes into account two internal forces that act on the intervertebral disk by their actions, contributing to the pressure exerted on the disk. These force elements are the erector spinae action and the abdominal pressure. As seen in Figure 3 which is adapted from Schultz and Andersson, the forces act at the low back level at L5/S1. We then have S_P, S_L—posterior and lateral shear forces; F_M—erector spine muscle force; F_C—disc compression force; A—rectus abdominus force; F_A—abdominal pressure resultant force;

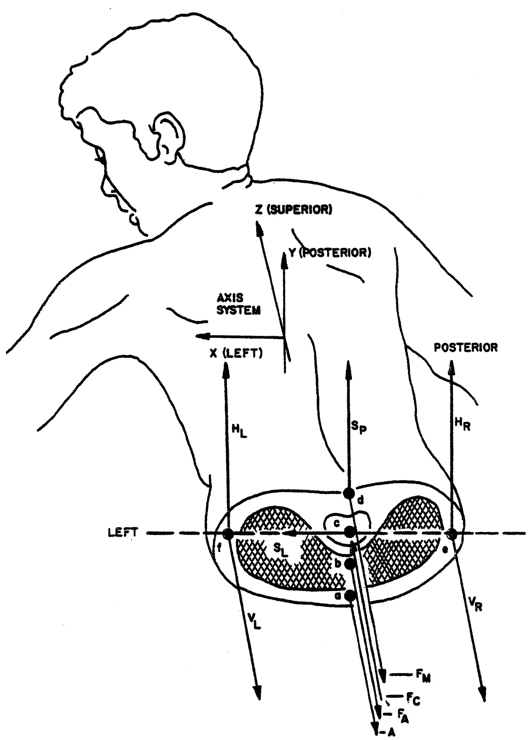


Figure 3. Active forces at L5/S1 in the lifting act, a three-dimensional low back model from Schultz and Andersson (1981).

V_R, H_R—vertical and horizontal components of the lateral abdominal wall muscle forces on the right side; V_L, H_L—vertical and horizontal components of the lateral abdominal muscle forces on the left side.

The principle guiding in applying the model is that to achieve a body balance at a given posture an equilibrium between the internal and external forces must be obtained, so is about the moment resulting from the acting forces. To calculate the moments, we relate to the reference points a to f as seen in Figure 3. Points a, b, c, and d are all on the same horizontal line at the midsagittal plane. Points e and f are located on the right (posterior) and left proximal sides of the abdomen, points e, c, and f are on the same horizontal line at the midcoronal frontal plane. All points are on the X–Y plane, the distances vary according to personal anthropometry.

We can obtain the values for the distances ac, bc, ec, and fc from anthropometric data sources (Gilad & Nissan, 1984). The following distance values have been found, these are average values: ac = 17 cm, bc = 11 cm, ce = cf = 16 cm. This enables to solve the following equilibrium equations,

$$
\begin{aligned}
F_X &= S_L,\\
F_Y &= H_R + H_L + S_P,\\
F_Z &= F_C + F_A - F_M - A - V_L - V_R,\\
M_X &= A \bullet ac - F_A \bullet bc - FM \bullet cd,\\
M_Y &= V_L \bullet cf - V_R \bullet ce,\\
M_Z &= H_L \bullet cf - H_R \bullet ce.
\end{aligned}
$$

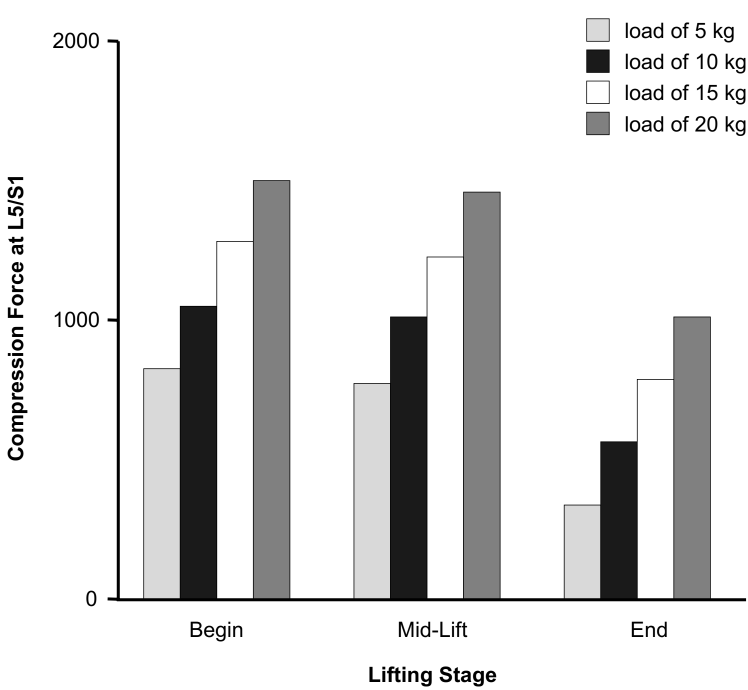
We now obtain a system with six equations and 10 unknowns variables. To solve this system, some of the variables need to be controlled. Thus we assume that the sign of a moment will decide which of the internal forces is acting, its opposite will be zero, if

$$
\begin{aligned}
&M_X > 0 \text{ then } & F_M &= 0,\\
&M_X < 0 & A &= 0,\\
&M_Y > 0 & V_R &= 0,\\
&M_Y < 0 & V_L &= 0,\\
&M_Z > 0 & H_R &= 0,\\
&M_Z < 0 & H_L &= 0.
\end{aligned}
$$

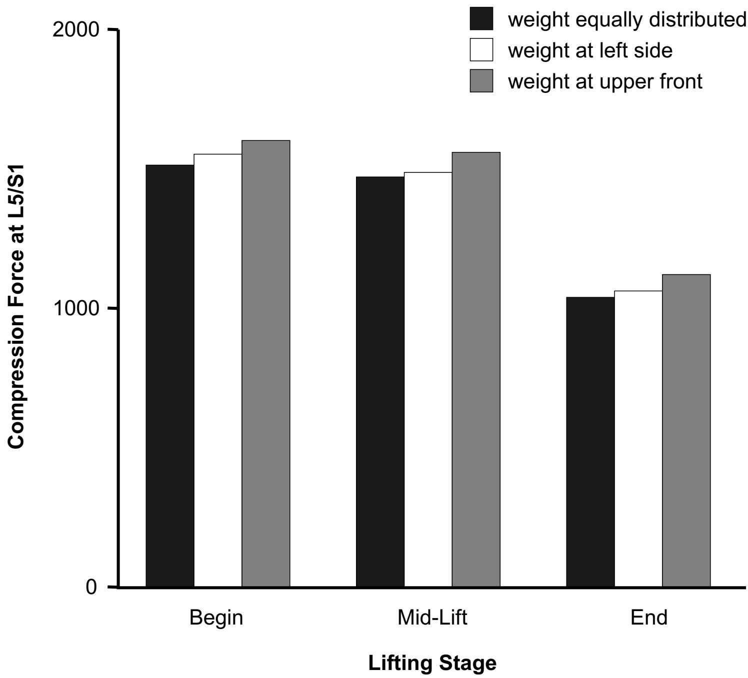
F_A, the abdominal pressure effect is empirically predicted (Chaffin & Andersson, 1999). We have the system reduced to six equations with six unknowns that can be solved with standard methods. This calculation provides us with the compression and the shear force acting at the L5/S1 level. According to the NIOSH (1981) lifting guide recommendations to control lifting hazards present a set of equations to the calculation of the weight for a safe lift. The equations used in the model refer to the 1981 guide, where AL and MPL are calculated. This approach enables the user to double-check the results he or she obtained from the simulation.

3. RESULTS

To test the presented model an analysis was conducted on a real-life material-handling act. The lifting act was demonstrated by a subject lifting a weight at an unconstrained posture at a regular working pace in an industrial setup. Different weights and distributions of the load were checked, in order to simulate the influence of distribution changes and load increase on the internal and external forces acting on the L5/S1 disk. Four different weights were used, 5, 10, 15, and 20 kg. Three different weight distributions were used, equally distributed, weight on the left side of the load, weight on the up front part of the load. Figure 4 demonstrates the findings of the analysis for the compression force at the L5/S1 disk, as obtained from the



Figures 4. Compression force at the L5/S1 disk, for four lifting loads equally distributed in the box.



Figures 5. Compression forces at the L5/S1 disk, when loads of 20 kg are differently distributed throughout the load box.

four lifting loads when equally distributed throughout the load box. Figure 5 shows the results of the analysis for the compression force on the disk, when three loads each of 20 kg are differently distributed throughout the load box.

The results of the experiment that were conducted as a case study to test the model, have been found to be consistent with the assumptions made at the beginning of the research. Namely that the load distribution influences the external and internal forces acting on the lower lumbar disk. The Lifter model at this point, is not able to quantify exactly this influence because the study was done for the purpose of demonstrating that there is in fact a difference according to load distribution.

Further research should be done in this direction in order to proceed with our approach. Efforts should be made on the way to define a distribution function that may include as a parameter the change in forces and moments as a result of a change in the load distribution. Another result was the consistency of the results found by NIOSH recommendations, in accordance with the compression and shear force on the L5/S1 disk.

4. DISCUSSION

Considerable research efforts in the area of manual materials handling have been directed toward establishing safety limits to manual lifting, ergonomic job design, employee placement, and employee training. Most of the studies were directed at symmetrical load handling where a load is moved in the midsagittal plane with both hands. As stated by Karwowski, Caldwell, and Gaddie (1994), who addressed the issue of the implication of NIOSH lifting guide (1981) in the design of lifting tasks. The authors refer to the non-solved problem when asymmetry of compressing and shear forces occurs due to lifting in a non-symmetrical act. Due to the complexity associated with three-dimensional force's analysis, studies of asymmetric load handling are few. The research effort can be complemented by this study, which is aimed at the analysis of non-symmetrical lifting by means of load homogeneity. The software that was developed from the theoretical model is easy to use, and may serve as a practical tool powerful enough for a large variety of users such as ergonomists, work designers, safety and medical personnel.

The combination of the theoretical model and the software introduced adds a required dimension to the field of lifting evaluation by letting the user simulate different parameters of a lifting act and redesign the lift job by changing the distribution of the weight or the worker posture. To conclude, the model met the expectations we put on it at the beginning of the study but it only opens the door to new directions for future lifting research.

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