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Lifter, a Computerized Lifting Analysis Technique

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Lifter, a Computerized Lifting Analysis Technique

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A computer driven technique to analyze lifting forces, in non-homogeneous load situations, is described and tested. Analysis is based on a dynamic algorithm aimed to evaluate unconstrained lifting posture and non-homogeneous content of loads. For inputs we use actual geometrical body postures in the form of 3-dimensional co-ordinates obtained from pictures taken at a work site. The outputs show a good match between the findings and pre-study assumptions for balanced and non-balanced load lifting practice. The results of the experiments show a good degree of correlation with results reported by researchers for symmetrical lifting tasks and with National Institute for Occupational Health (NIOSH) lifting guidelines. It is believed that the technique can serve as the proper choice for industrial and safety analysts of lifting activities.

non-homogeneous loads   lifting model   weight distribution

1. INTRODUCTION

Lifting non-homogeneous loads or unbalanced objects is common to many industrial tasks. Many jobs require manual handling of materials that require non-symmetrical lifting as a daily occupational activity. The act of lifting results in the transfer of significant stresses to the spine and the back muscles; exertion of strength during the act of manual lifting is the basic generator of work injuries. Overexertion is claimed to be the cause of low back pain by over 60% of the people suffering from it. According to Kumar

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(2001), about 55% of overexertion injury claims involved load lifting. The risks involved in overexertion are not always taken into account by workers, managers, or task designers. Therefore a constant effort is needed to search, understand, simulate, and analyze the acts of lifting in the real occupational situation in order to reduce the hazard level of overexertion due to lifting tasks.

Biomechanical models were developed in order to quantify the occupational risk level; the two-dimensional model performs a static force analysis in the sagittal plane (Chaffin, 1969). This model based on forces and moments conservation equations was primeval, but it has been found to calculate a good approximation of the external forces acting at each joint. Few models involving dynamic three-dimensional lifting analysis have been developed and they are listed in Chaffin and Andersson (1999). A fairly known one is the three-dimensional static strength prediction model by Chaffin and Erig (1989). In those models, only limited research effort has been dedicated to handling non-homogeneous loads. A biomechanical low back model by Shultz, Andersson, Ortengren, Nachemson, and Haderspeck (1982) accounting for the internal forces acting at the low back level and specifically at the L5/S1 disk level, is a good predictor for the exertion of forces on the lower spine. Studies of asymmetric load handling are fairly rare, the general reason according to these authors is the complexity associated with three-dimensional force analysis, and the wide description of the variety of loads, which contributes to the asymmetry of lifting.

It may be concluded that, although non-symmetrical load handling influences performance strength and can result in postural instability and back trauma, research has not yet provided a simple enough and comprehensive tool to evaluate this kind of load lifting. From monitoring scientific literature, it is interesting that relatively limited research has been conducted on the subject of load design; this study has been more concentrated on the amelioration of lifting postures.

2. METHODOLOGY

From a biomechanical point of view, studies of lifting are mainly interested in the pressure exerted on the disk. This pressure can be decomposed into two components: compression force, which is the force acting perpendicular to the plane of the disk and toward its center, and the shear force, which is the force acting in parallel to the plane of the disk from its center to outside. When computers became more popular, researchers were eager to test their models on computers and created software to analyze lifting tasks. Chaffin (1969) made one of the first attempts to create a computerized model on a mainframe. Later on, Garg and Chaffin (1975) developed a simulation of the human strength during lifting operations. A popular model today is the Two Dimensional Static Strength Model Prediction Program, developed at the University of Michigan (1990), which calculates the strength capability of a participant for a specific posture according to the population group he or she belongs to. A noticed inconvenience of this software is that it does not deal with the internal forces acting at the low back level but rather with the external forces at each joint in the body. Moreover it can analyze only one posture at a time, whereas a lifting task is composed of many postures. The number of postures needed for the analyses can be reduced, but one is certainly not representative of a lifting task. The major disadvantage of mainframe-based software is the problem of having a mainframe computer handy, and then learning how to use it. It usually takes some training before one is able to work smoothly with one of these machines.

While analyzing lifting tasks, one can wonder how to record the action faithfully in order to correctly analyze the posture involved in the lift. Two-dimensional analysis is rather simple and one camera is enough to record the postures to analyze with a use of a digitizer, joint co-ordinates can be recorded in the sagittal plane and entered into a model. Three-dimensional analysis is more complex, and one needs to record two views of a posture at the same time. Ayoub (1972) proposed a solution based on two cameras placed perpendicularly to each other while recording at the same time. Andriacchi, Hampton, Shultz, and Galante (1979) used a similar method, reporting good results.

Although these methods give good results they need considerable attention and care, not only because of the synchronization needed, but also because of the corrections needed to adjust the results. Those could have been distorted by the lenses of the cameras or the perpendicularity of the shooting planes of the cameras. Another problem is the cost of such a solution and the room needed to implement it properly. It is our understanding that lifting analysis should take place at the work site, in order to work out simulations and deliver solutions under real constraints. We may therefore say that a simple three-dimensional monitoring method is still needed for modeling the spine and enabling on-site lifting analysis.

The theoretical model used in the Lifter protocol is composed of four submodels, each one interacting with the other, whereas the results expected are the external and internal forces acting on the L5/S1 intervertebral disk and the National Institute for Occupational Health (NIOSH) guidelines for manual lifting. The model was developed in order to answer a wide range of problems caused by lifting analysis. The four submodels are the load model, the three-dimensional body segment model, the low back internal forces, and NIOSH (1981) lifting guidelines, which will be briefly described. The load model assumes the load as an object that can be put into a rectangular box of known dimensions.

2.1. Description of the Technique

The lifted load is defined as a box divided into 32 cubes of identical dimensions, each cube has a weight made of homogeneous material, so its center of mass is at the center of the cube. The division into cubes allows the user to define the weight distribution in the load so that a non-homogeneous load can be designed if required by the task. The box can be grasped anywhere, with or without handles. This definition makes it easy to calculate the location of the center of mass of the load and the forces and moments acting at the hand level. Once these data have been calculated they are passed through to the three-dimensional segment model in order to calculate the forces and moments at each joint, especially at the L5/S1 level.

In this three-dimensional model the body is represented as a set of 15 segments linked by its theoretical joints; on each segment the force and moment conservation laws apply. It is therefore fairly easy to calculate the forces and moments applying at each joint starting from the hand through the arms, summarize the forces and moments of each arm at the neck, and then calculate the external forces and moments at the L5/S1 level. The model calculates the angles of the thigh and the torso to allow the user to compare these figures with the forces applying at the L5/S1 level, and to determine when a certain angle can be hazardous. The results found are passed on to the internal low back force model in order to find the internal forces acting at the L5/S1 level. Although this is a classical model, it is powerful enough as we deal with static analysis.

The location of the joints involved was previously found by a task recording process, as will be further explained in this paper. Three-dimensional force and moment conservation equations are of equal complexity to those for two dimensions, but the main difference resides in the fact that equations must be solved for each of the three axes (X, Y, Z). The low back model as developed by Shultz et al. (1982) uses several parameters that had not been accounted before. The model assumes that whenever a lift occurs, the back muscles (erector spinae) and the abdomen react by applying forces around the L5/S1 disk. These forces counterbalance the effects of the external forces, and the moment they create around the spine compensates the external moments.

A system of six equilibrium equations is then written and solved. The solution is not obvious as there are 10 unknowns to find, but we can control some of the variables by setting them to zero when there is no moment created by that force. In this way three unknowns are removed and a fourth (abdominal pressure) is empirically calculated. The system can than be easily solved, and the compression and the shear force at the L5/S1 are calculated. To support the model with safety recommendations, the NIOSH guide published in 1981 is used. These recommendations refer to the symmetrical two-handed lifting of loads as related to the sagittal plane. Although the new version of the NIOSH guide was published in 1994, we have decided to relate in this paper to the well-accepted 1981 guidelines. According to the distance of the load from the floor to the L5/S1 disk, a recommendation is made about what would be a safe load in that posture.

The recommendation takes the form of the accepted two values; AL (Action Limit) representing the safe weight at a given posture for 99% of the men and 75% of the women, and MPL (Maximum Permissible Limit) representing the safe weight at a given posture for 33% of the men and 1% of the women. MPL is defined as being 3 times AL. These values advise the user how to choose the weight of the load to design a safe lifting task.

2.2. The Lifting Analysis

Two sets of lifting were studied to validate the software. In the two studies a young male was requested to lift a box measuring 40 × 30 × 20 cm. In the first study the box was loaded with four different loads, the participant lifted 5, 10, 15, and 20 kg in four trials. In the second study the box contained a variable weight distribution; 20-kg weights were lifted in three different combination of weight distribution, equally distributed, weight concentrated on the left side of the load, and weight concentrated on the up-front part of the load. The test site was so arranged that the frontal and sagittal planes were captured in the focus of one camera (Figure 1). The participant performed his lifting acts in front of a 180 × 100 cm mirror, the video camera was placed in perpendicular form to the sagittal view to capture both the participant and his image in the mirror. The participant's joints were marked with light-reflecting reference marks to be seen in both plane views.

The participant was filmed while lifting the load in his preferred posture, imitating his most natural working pace, supporting the box in his preferred grasping points. From the video-recorded frames a lifting sequence was chosen where all markers could be clearly seen, three frames were selected to be analyzed. The selected frames were to represent the lift in its entirety. The first frame was taken at the beginning of the lift, where the load was still on the floor. The second one in a middle phase of the lifting act, where the load reached half way of the total lift height. The third was where the participant and the load reached the final destination.

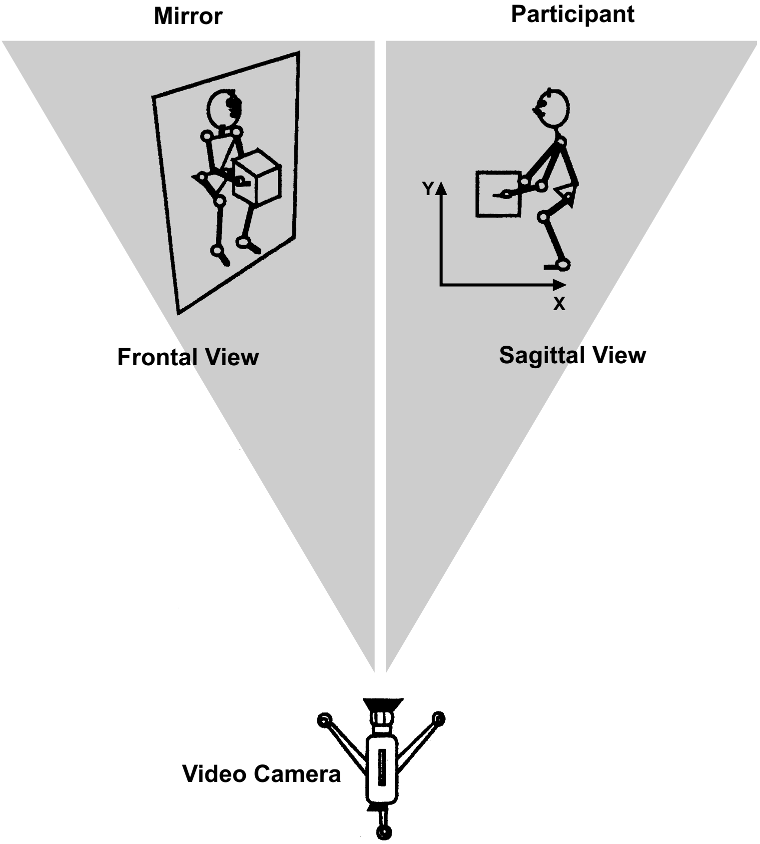


Figure 1. Lifting experiment setup.

Using a transparent sheet marker locations were recorded from the monitor screen. We then measured the location of each of the joints in each of the two planes. Once the co-ordinates had been recorded in both front and sagittal planes, they were combined to get a single three-dimensional co-ordinate for each joint on every frame; these co-ordinates were recorded and analyzed by the Lifter Software.

3. RESULTS

The 12 combinations of the lifting loads and weight distribution as demonstrated in the experiment were fed into the software and a lift analysis was performed. The results are summarized in Tables 1, 2, 3, 4, and 5. The legend is as follows: $C_{I,J}$ is the lift combination for lifting loads I and weight distributions J. For lifting load I_1 the weight is 5 kg, for I_2 10 kg, for I_3 15 kg, for I_4 20 kg. The weight distributions are, for J_1 the weight is equally distributed, for J_2 the weight is concentrated on the left side, for J_3 the weight is concentrated on the upper front part of the load.

Table 1 contains the external forces recorded for each posture. Table 2 presents the external moments calculated at each posture. Table 3 gives the

TABLE 1. External Forces Recorded for Each Posture

Combination	F_X (N)			F_Y (N)			F_Z (N)		
	Frame 1	Frame 2	Frame 3	Frame 1	Frame 2	Frame 3	Frame 1	Frame 2	Frame 3
$C_{1,1}$	0.0	0.0	0.0	–454.2	–394.7	6.2	–253.5	–338.7	–520.1
$C_{1,2}$	0.0	0.0	0.0	–454.2	–394.7	6.2	–253.5	–338.7	–520.1
$C_{1,3}$	0.0	0.0	0.0	–454.2	–394.7	6.2	–253.5	–338.7	–520.1
$C_{2,1}$	0.0	0.0	0.0	–497.0	–431.9	6.8	–277.4	–370.7	–569.1
$C_{2,2}$	0.0	0.0	0.0	–497.0	–431.9	6.8	–277.4	–370.7	–569.1
$C_{2,3}$	0.0	0.0	0.0	–497.0	–431.9	6.8	–277.4	–370.7	–569.1
$C_{3,1}$	0.0	0.0	0.0	–539.8	–469.2	7.4	–301.3	–402.6	–618.2
$C_{3,2}$	0.0	0.0	0.0	–539.8	–469.2	7.4	–301.3	–402.6	–618.2
$C_{3,3}$	0.0	0.0	0.0	–539.8	–469.2	7.4	–301.3	–402.6	–618.2
$C_{4,1}$	0.0	0.0	0.0	–582.7	–506.4	8.0	–325.2	–434.5	–667.2
$C_{4,2}$	0.0	0.0	0.0	–582.7	–506.4	8.0	–325.2	–434.5	–667.2
$C_{4,3}$	0.0	0.0	0.0	–582.7	–506.4	8.0	–325.2	–434.5	–667.2

Notes. X, Y, Z—axes.

TABLE 2. External Moments Calculated at Each Posture

Combination	F_X (N)			F_Y (N)			F_Z (N)		
	Frame 1	Frame 2	Frame 3	Frame 1	Frame 2	Frame 3	Frame 1	Frame 2	Frame 3
$C_{1,1}$	116.8	111.2	34.0	–22.3	–23.0	–24.7	39.9	28.6	–0.3
$C_{1,2}$	117.7	111.2	34.0	–23.2	–23.8	–25.6	41.5	27.8	–0.3
$C_{1,2}$	120.0	114.9	37.6	–22.6	–23.0	–24.7	40.6	26.8	–0.3
$C_{2,1}$	143.9	139.1	55.4	–32.5	–35.0	–42.1	58.1	40.8	–0.5
$C_{2,2}$	145.0	139.1	55.4	–34.3	–36.7	–44.0	61.4	42.8	–0.5
$C_{2,3}$	151.1	146.5	62.7	–33.2	–35.0	–42.1	59.5	40.8	–0.5
$C_{3,1}$	171.0	167.0	76.8	–42.6	–47.1	–59.6	76.4	54.9	–0.7
$C_{3,2}$	173.6	167.0	76.8	–45.4	–49.6	–62.4	81.1	57.8	–0.7
$C_{3,3}$	181.8	178.1	87.8	–43.8	–47.1	–59.6	78.4	54.9	–0.7
$C_{4,1}$	198.0	194.9	98.2	–52.8	–59.1	–77.0	94.6	68.9	–0.7
$C_{4,2}$	201.5	194.9	98.2	–56.4	–62.5	–80.8	101.1	72.8	–1.0
$C_{4,3}$	212.4	209.6	113.0	–54.4	–59.1	–77.0	97.4	68.9	–0.9

Notes. X, Y, *Z*—axes.

TABLE 3. Compression and Shear Forces

Combination	Compression Force			Shear Force		
	Frame 1	Frame 2	Frame 3	Frame 1	Frame 2	Frame 3
$C_{1,1}$	831.0	781.0	349.0	703.0	562.0	4.0
$C_{1,2}$	842.0	786.0	355.0	714.0	568.0	4.0
$C_{1,3}$	855.0	802.0	370.0	708.0	562.0	4.0
$C_{2,1}$	1057.0	1012.0	577.0	860.0	687.0	4.0
$C_{2,2}$	1079.0	1022.0	589.0	881.0	699.0	4.0
$C_{2,3}$	1105.0	1052.0	617.0	869.0	687.0	4.0
$C_{3,1}$	1283.0	1240.0	802.0	1017.0	812.0	4.0
$C_{3,2}$	1316.0	1255.0	820.0	1048.0	830.0	4.0
$C_{3,3}$	1355.0	1310.0	861.0	1030.0	812.0	4.0
$C_{4,1}$	1509.0	1467.0	1025.0	1174.0	937.0	4.0
$C_{4,2}$	1553.0	1488.0	1048.0	1215.0	961.0	4.0
$C_{4,3}$	1605.0	1548.0	1102.0	1191.0	937.0	4.0

compression and shear force, Table 4 shows the thigh and torso angles as measured from the geometrical configurations. Table 5 presents the findings obtained for AL and MPL recommendations for lifting control relating to the vertical, horizontal, and travel distances.

TABLE 4. Thigh and Torso Angles

Angle	Frame 1	Frame 2	Frame 3
Torso	42.2°	36.5°	3.4°
Thigh	88.3°	40.8°	2.6°

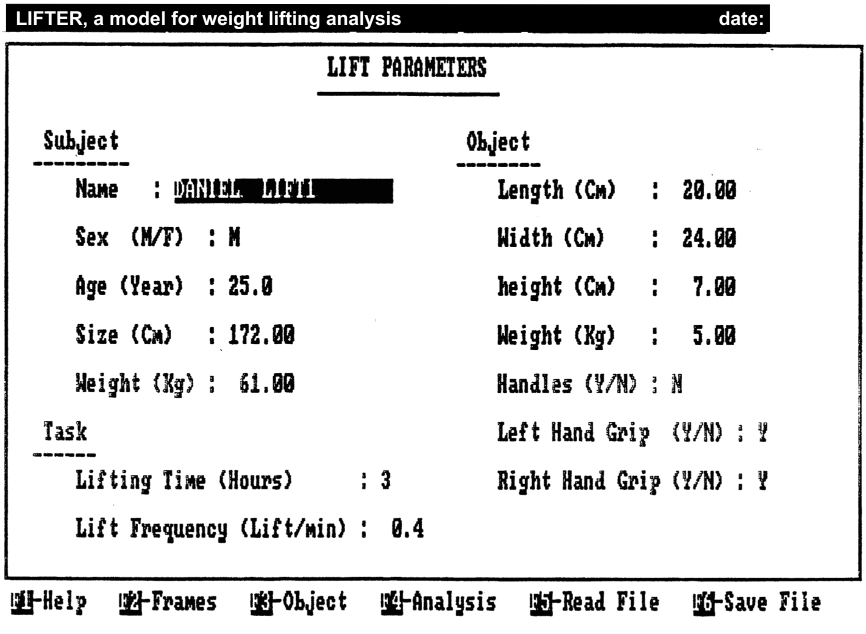
TABLE 5. Findings Obtained for AL and MPL Recommendations

Lifting Parameters	Frame 1	Frame 2	Frame 3
V (cm)	11.1	11.1	16.1
H (cm)	62.4	68.3	71.4
D (cm)	94.3	94.3	94.3
AL (N)	53.0	48.6	47.7
MPL (N)	159.0	145.8	143.1

Notes. V—vertical location, H—horizontal location, D—distance the load is lifted, AL—Action Limit, MPL—Maximum Permissible Limit.

3.1. The Lifter Software

The Lifter software is intended to be an active tool in lifting analysis as it can provide immediate results, and thus allow the user to make necessary



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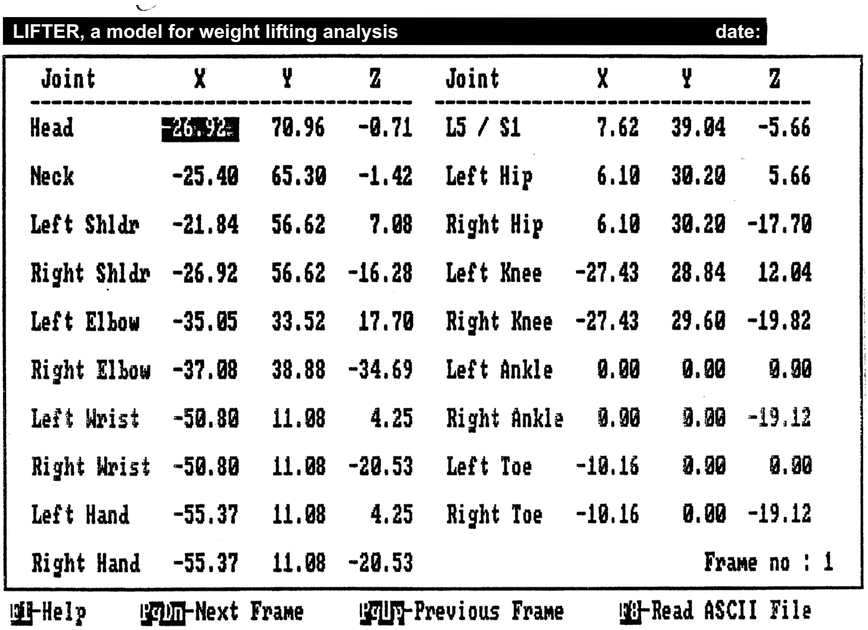
LIFTER, a model for weight lifting analysis                    date:

                            LIFT PARAMETERS

 Subject                                Object
 ---------                              --------
    Name      : [redacted]                 Length (Cm)     :  20.00
    Sex  (M/F)  : M                        Width (Cm)      :  24.00
    Age (Year)  : 25.0                     height (Cm)     :   7.00
    Size (Cm)   : 172.00                   Weight (Kg)     :   5.00
    Weight (Kg) :  61.00                   Handles (Y/N) : N
 Task                                      Left Hand Grip  (Y/N) : Y
 ------
    Lifting Time (Hours)      : 3          Right Hand Grip (Y/N) : Y
    Lift Frequency (Lift/min) :  0.4
```

Figure 2. Lifting parameters input screen.



Joint	X	Y	Z	Joint	X	Y	Z
Head	-26.92	70.96	-0.71	L5 / S1	7.62	39.04	-5.66
Neck	-25.40	65.30	-1.42	Left Hip	6.10	30.20	5.66
Left Shldr	-21.84	56.62	7.08	Right Hip	6.10	30.20	-17.70
Right Shldr	-26.92	56.62	-16.28	Left Knee	-27.43	28.84	12.04
Left Elbow	-35.05	33.52	17.70	Right Knee	-27.43	29.60	-19.82
Right Elbow	-37.08	38.88	-34.69	Left Ankle	0.00	0.00	0.00
Left Wrist	-50.80	11.08	4.25	Right Ankle	0.00	0.00	-19.12
Right Wrist	-50.80	11.08	-20.53	Left Toe	-10.16	0.00	0.00
Left Hand	-55.37	11.08	4.25	Right Toe	-10.16	0.00	-19.12
Right Hand	-55.37	11.08	-20.53				

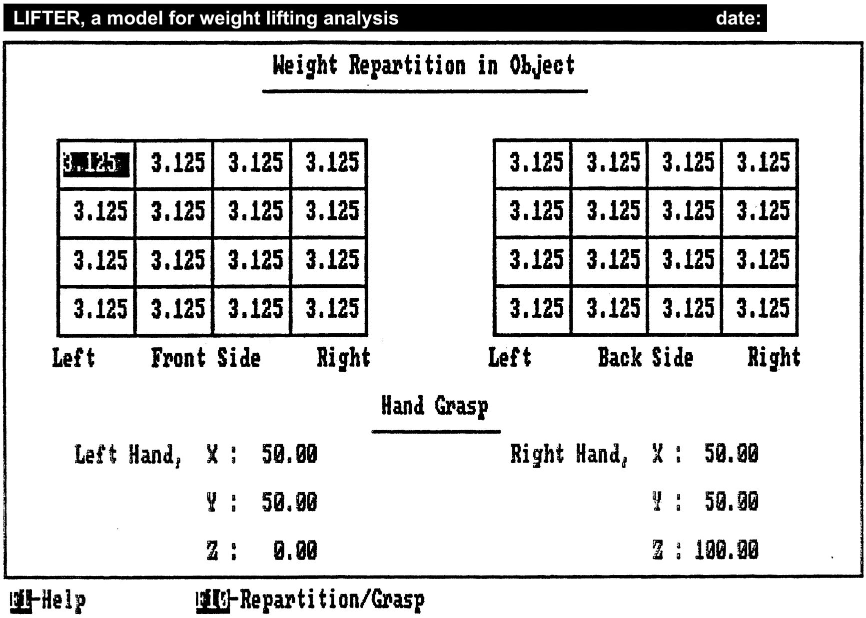
Frame no : 1

Figure 3. Body posture as defined by joint co-ordinates for each of the two plane views.

adjustments to the task to make it safer. Lifter is divided into three parts: input screen, output screen, and algorithm. To provide easy access to the tool, a user-friendly machine interface was developed, which provided an efficient way for the user to enter data. Figure 2 shows the lift parameters input screen. It includes general information about the participant, the task, and the object to be lifted. This information can be edited or changed online. Figure 3 is the entry data of the body posture as joint co-ordinates for each of the two plane views. To ease this process, a routine can be called to read a previously prepared ASCII file containing the co-ordinates. These co-ordinates are critical as they define the body posture in each of the three frames representing the lift.

Figure 4 represents the data about the weight distribution and the geometry of the preferred grasping point. In each cube, the number represents the percentage of the total weight contained in the cube, in this case the load in the box is equally distributed. Grasping points are entered as percentage of the size of the box.

After input data has been entered, the program calculates the forces and moments applying at the hand, then calculates the external forces and



LIFTER, a model for weight lifting analysis date:

Weight Repartition in Object

3.125	3.125	3.125	3.125
3.125	3.125	3.125	3.125
3.125	3.125	3.125	3.125
3.125	3.125	3.125	3.125

Left Front Side Right

3.125	3.125	3.125	3.125
3.125	3.125	3.125	3.125
3.125	3.125	3.125	3.125
3.125	3.125	3.125	3.125

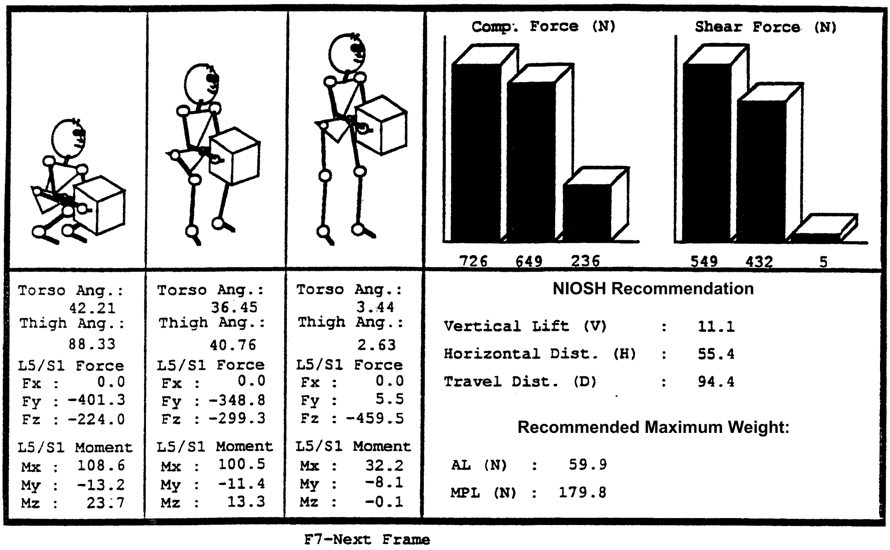
Left Back Side Right

Hand Grasp

Left Hand, X : 50.00
Y : 50.00
Z : 0.00

Right Hand, X : 50.00
Y : 50.00
Z : 100.00

Figure 4. Weight distribution and holding points.



Torso Ang.: 42.21	Torso Ang.: 36.45	Torso Ang.: 3.44
Thigh Ang.: 88.33	Thigh Ang.: 40.76	Thigh Ang.: 2.63
L5/S1 Force	L5/S1 Force	L5/S1 Force
Fx : 0.0	Fx : 0.0	Fx : 0.0
Fy : -401.3	Fy : -348.8	Fy : 5.5
Fz : -224.0	Fz : -299.3	Fz : -459.5
L5/S1 Moment	L5/S1 Moment	L5/S1 Moment
Mx : 108.6	Mx : 100.5	Mx : 32.2
My : -13.2	My : -11.4	My : -8.1
Mz : 23.7	Mz : 13.3	Mz : -0.1

NIOSH Recommendation

Vertical Lift (V) : 11.1
Horizontal Dist. (H) : 55.4
Travel Dist. (D) : 94.4

Recommended Maximum Weight:

AL (N) : 59.9
MPL (N) : 179.8

Figure 5. Analysis screen as computed for a given lifting. *Notes.* Ang.—angle, Comp.—compression, dist.—distance; X, Y, Z—axes.

moments at the disk level, and finally calculates the compression and the shear force at the L5/S1 level. The AL and MPL are calculated from the postures of which the data is present in Figure 3. Figure 5 demonstrates the results as computed for a given lifting, the analysis screen is divided into four subframes. In the left two frames the three momentary body configurations as a stick diagram are seen with their geometrical definitions under each configuration.

The stick diagrams can be spanned around a vertical axis to allow a check of any default in the position of the body during the lift. For each posture, thigh and torso angles, external forces, and moments are presented. The bar graph on the upper right presents the evolution of the compression and the shear forces during the lifting act at the L5/S1 level. Lifting recommendations according to NIOSH guidelines are presented in the lower right frame. The data obtained can be saved into a lifting file for comparison or any further use.

4. DISCUSSION

PC-based Lifter software was developed to support the lifting model. Two main objectives were set at the beginning of the study. One was to evaluate how weight distribution influences the external and internal forces as they act at the L5/S1. The other was to develop a relatively simple and effective tool for the analysis of lifting performance that considers loads of variable weight distribution. The first set of findings as reported in Boughanim and Gilad (1992) demonstrated how increasing the lifting load sensibly increases the external force acting on the lifter's spine at the L5/S1 intervertebral disk. These results are consistent with the results found by Kromodihardjo and Mital (1987). Other components of the forces and the external moment, as well as the compression and the shear force, rise significantly when the weight is lifted. These results are also a partial proof for the acceptance of the evaluation methodology and the Lifter software accuracy when lifting tasks are to be analyzed. When the weight is not equally distributed in the load to be lifted, the internal forces and the moments at the intervertebral disk are subject to an increase.

Further research is needed in order to quantify the changes in compression and shear forces when the weight suddenly becomes unbalanced, when lifting fluids, for example. It is our opinion that the currently used methods do not give the user an immediate answer and more research might help to enrich the methodology used for the evaluation of lifting.

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