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Neeraj Saraswat
Dayalbagh Education Institute, Agra-282110, India,, neeraj7946@gmail.com

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Analysis of a Biomechanical Model for Safe Lifting using MATLAB Simulation

Neeraj Saraswat[1], Shikhar Sharma[2], Rahul Jain[3] & Deepak Pathak[4]

[1&2]Dayalbagh Education Institute, Agra-282110, India, [3&4]FET Agra College, Agra, India
E-mail : neeraj7946@gmail.com[1]

Abstract - This paper describes the development of a multi-body biomechanical model that can be used to assess the risk of low back disorders. A multi-segment link model is considered in this paper which represents a human body in which links represent various limbs such as arms, leg, foot, thigh, thorax etc. Force balance and moment balance equations are formed at different joints. Equations formed are written in form of a MATLAB program to determine the relationship between load lifted and muscle moment generated due to load. This biomechanical model was employed to clarify the role of various biomechanical factors such as magnitude of load, shape, size and location of load involved in the load lifting process. To determine safe lifting postures on the basis of model such that the reaction force at the L4 / L5 joint is minimum subjected to other joints not being overstressed is carried out. Various moment-load relationships between various joints are computed along with moment-moment relationships between various joints. The model is able to suggest the safe posture in manual material handling tasks. A geometric model for simulations of postural control is obtained with Matlab/Simulink software.

Keywords - Multi-Segment link Model , Load lifting, Manual Material Handling (MMH), MATLAB.

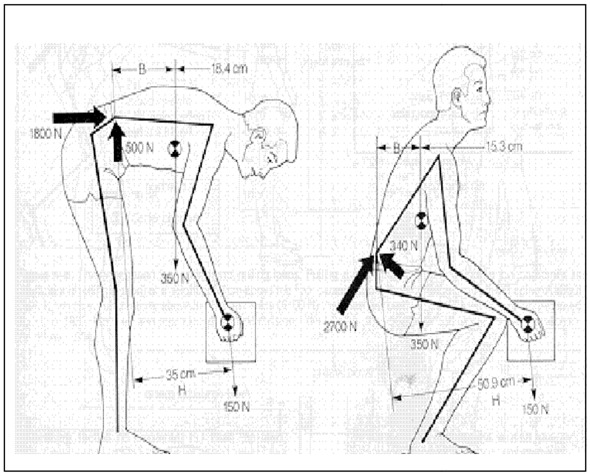
I. INTRODUCTION

Humans have evolved over millions of years to be what they are today. The evolutionary pressure and consequent speciation resulted in an upright biped creature with dexterous upper limbs and highly evolved brain. For the large duration of its existence, the species relied on hunting and gathering as its primary means of sustenance. With the advancement of science, technology and industrialization, the physical occupational stresses have changed dramatically. Thus none of the body systems that one uses today occupationally was either designed or evolved for the purpose. As such, demand for force exertion, repetition of activities, or assuming postures for prolonged periods places stress on human physical systems, which is inherently unnatural.

Thus humans are neither anatomically adapted to withstand the modern physical industrial demands nor are they mentally suited to endure such psychological stresses. This results in various kinds of accidents with personal injuries. For a meaningful attempt to control such injuries we have to understand the types of activities. Lifting materials manually constitutes a major work activity in most industrial workplaces. Despite the trend towards automation a large proportion of industrial activity in future is expected to remain to be handled manually.

Load lifting is the main source of various musculo-skeletal injuries, especially low back problems. Which lies under the category of Manual Material Handling (MMH). Lifting involves the various human joints in a complex manner. During load lifting the force applied by the load to be lifted is distributed to the low back, hip and knee joints, but their relative proportions of sharing may depend on various factors such as age, sex, strength of various involved muscles, mass of the object, and posture adopted. But the main determining factor appears to be the posture adopted during lifting.

The current practice states that worker should bend at the knees while lifting low lying objects so that they can avoid or reduce back injuries and low back problems. There is indeed a need to determine optimal working posture for various situations of load shifting. In industrial workplaces, the biomechanical model can provide a guide to the workplace design in terms of manual material handling activities, especially the lifting tasks. Model predictions combined with worker's anthropometric characteristics can considerably reduce low back injuries in the workplace.



II. MANUAL MATERIAL HANDDING (MMH)

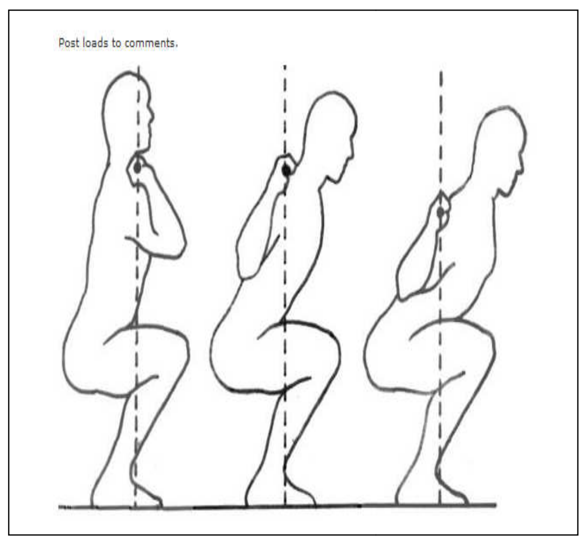
Manual material handling (MMH) has been considered as a major occupational hazard to workers (Ayoub et al., 1987). Of the various MMH tasks, load lifting is thought to be the primary source of various musculo-skeletal injuries, especially low back problems. Over-exertion appears to be the main reason for these injuries (BLS, 1982). Current estimates of musculo-skeletal injuries due to over-exertion put the figure at about 34 % of all types of injuries. Also about 25% of injuries are thought to be associated with the low back (BLS, 1982).

Lifting involves the various human joints in a complex manner. The external force applied by the load to be lifted is shared primarily by the low back, hip and knee joints, but their relative proportions of sharing may depend on various factors. Age, sex, strength of various involved muscles, mass of the object and posture adopted during lifting are some of the important factors affecting the lifting process. Of these, posture during lifting appears to be a crucial factor (Brown, 1971; Kumar, 1984).

It is perhaps due to this reason, that training on MMH tasks in industry emphasizes the role of correct postures which should be adopted by workers during lifting objects (NIOSH, 1981). Some authors (Bendix and Eid, 1983; Oudenhoven ey al., 1982) even suggested that the back should be held straight and vertical when lifting low lying objects. Such guidelines, however, ignore the fact that by making knee joints take up more load, there will be more workers suffering from knee joint injuries or problems. Besides, the validity of these guidelines have been questioned (Chaffin and Park, 1973). Graveling et al. (1985) have even suggested that the recommended safe lifting techniques are not realistic. There is indeed a need to determine optimal working postures for various situations of load shifting.

Many studies have been carried out to determine, using physiological and psychological methods, safe and perhaps optimal lifting techniques/postures. Parnianpour et al. (1987) have pointed out the fallacy of a single correct technique. They recommended different lifting techniques for individuals with different joint problems. Kumar (1984) has examined three different lifting postures (stoop lifting, squat lifting and free style lifting with no postural constraints) to determine which of these is optimal. From the subjective point of view, squat lifting was found to be more tiring than straight leg posture. In terms of physiological cost, the stoop method (bent back, straight legs) of lifting was found to be least and the squat method (flexed knee, straight back) most demanding. Recent studies (e.g. Schipplein et al., 1990) indicates that the safe or optimal lifting may indeed be determined the magnitude and / or location of loads.

From the above studies, it is clear that optimal lifting postures are as much a function of individual characteristics as of external constraints. To clarify the role of various parameters such as magnitude of load, individual anthropometric characteristics, shape, size and location of loads etc. in determining the optimal working postures, a model approach appears to be more reasonable, economic and less time consuming than experimental trials on human subjects.



III. METHODOLOGY

A multi-segment link model is considered for determining the joint moments and reactive forces during load lifting. Lifting of loads is restricted to the sagittal plane and a two- dimensional static analysis is carried out. The lifting is assumed to be symmetrical about mid sagittal plane.

3.1 MULTI-SEGMENT LINK MODEL

α = torso angle with the vertical axis

β = hip flexion angle

γ = thigh angle with the horizontal axis

δ = angle between the thigh and the leg

€ = angle between the foot and the leg

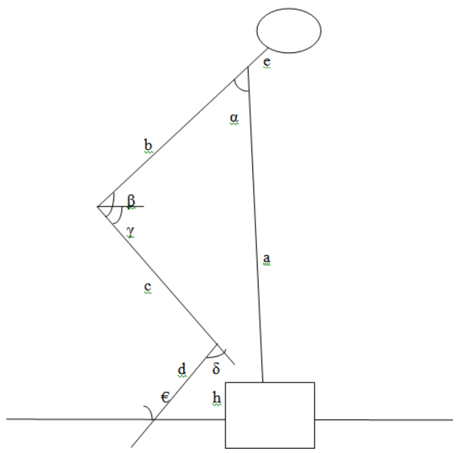


Fig. 1

These angles are interrelated by the following expressions :

$\gamma = 180 - € - \delta$

$\beta = \alpha - \gamma + 90$

For the determination of reaction forces, we need to set up the force and moment balance equations for the body. At each joint in consideration we have the x, y and z axis as defined in figure 1. A moment is defined to be positive/negative if the force acts posterior/anterior to the joint in concern.

3.2 L4/L5 JOINT :

At the L4/L5 joint, the moment balance equation is

$F_{es} * l_{Bes} = W_{tr} l_{btr} + W_a l_{Ba} + P*l_{Bp}$

Where:

F_{es} = force sustained by erector spine.

W_{tr} = Weight of thorax (including the head) above L4/L5 joint.

W_a = Weight of arms (upper arms + forearms including the hands).

P = Weight of load to be lifted.

Here l_{Bes}, l_{Btr} l_{Ba} l_{Bp} are respectively the lever arms of erector spinae muscle equivalent, W_{tr}, W_a and p respectively .

The force balance equations at the L4/L5 joint are approximately, assuming the L4/L5 joint is perpendicular to the hip-shoulder link:

$CB = F_{es} + (W_{tr} + W_a + p) * \cos \alpha$

$SB = (W_{tr} + W_a + p) * \sin \alpha$

Along the axis perpendicular to the compression axis, where CB and SB represent the compressive and shear force components of the joint reaction force, RB, that is,

$RB = (CB^2 + SB^2)^{1/2}$

This is the net reactive force at L4/L5 joint.

IV. SIMULATION

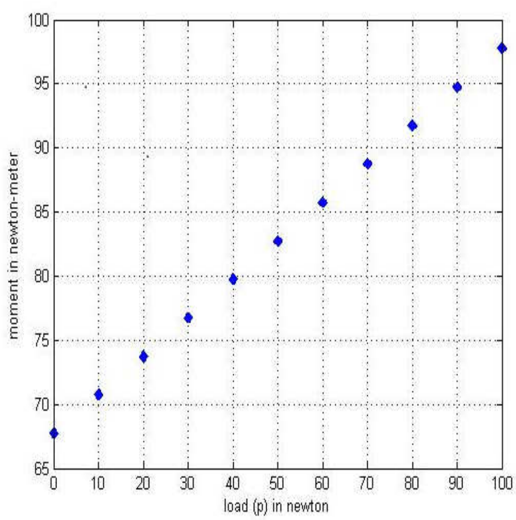
The non-linear set of algebraic equations describing force and moment balance at various joints together with their constraints, is solved for the muscle forces, the reactive forces and the feasible postural configurations. A computer program was written which calculated the joint reactive forces for acceptable body configurations. The angles δ and € were incremented by 2^0 from their minimum to maximum values, as listed in table 1. Computations were carried out for different external applied loads and heights from which the load was lifted, box width (in the sagittal plane) and positions of handles on the box.

V. SAFE WORKING POSTURES

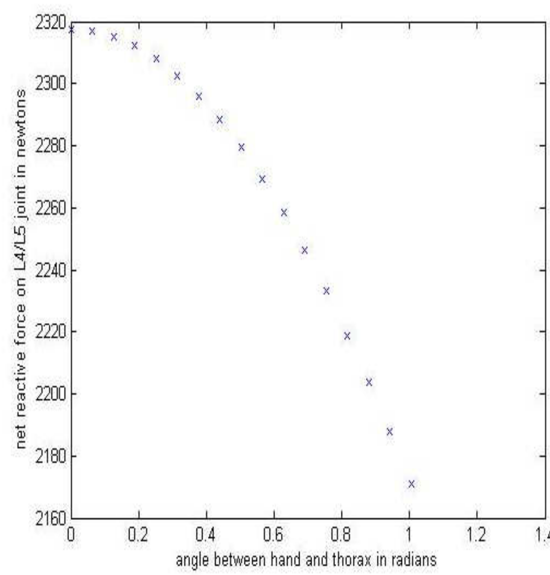
We are interested in safe working postures during load lifting. To obtain an safe working posture, a criterion or a set of criteria needs to be established. For example, An et al. (1984) proposed an objective function based on minimizing the upper bound for all of the muscle stresses. Crowninshield and Brand (1981) considered minimization of the sum of squares of muscle forces or muscle stresses as an appropriate cost function so that the task of endurance could be maximized. Bejjani et at. (1984) examined the possibility of using the ‘average body force’ (defined as the half of the sum of the low back and the knee joint reaction forces) for obtaining optimal working postures during lifting loads. An extension of the Bejjani’s cost function has been used by Noone and Mazumdar (1992) to predict optimal lifting postures. Schultz et al. (1983) considered minimizing muscle intensity together with spine and joint compression force.

In our model we have considered the minimization of the total compression force on the low back joint (L4/L5) assuming the stability of the body during the lifting process and the generated muscle forces and joint moments do not exceed the upper bound experimentally determined for each of the joints (Chaffin and Anderson, 1984) An safe working posture is considered with satisfies the above conditions for given model parameter values. An algorithm is in-built in the computer program to select the safe working posture from among all feasible posture configurations.

```
% Load-Moment relationship for L4/L5 Joint %
close all
clear all
lbes=0.05;%lever arm of erector spinae muscle equivalent
wtr=220;%weight of trunk
lbtr=0.25;%lever arm of C.G of trunk about L4/L5 joint
wa=42.5;%weight of arms in newton
lba=0.3;%lever arm of C.G of arms about L4/L5 joint
p=100;%load in newtons
lbp=0.3;%lever arm of C.G of load about L4/L5 joint
figure ;
for p=0:10:100
   moment=(wtr*lbtr+wa*lba+p*lbp);
   plot(p,moment,'x','LineWidth',5);
   xlabel('load (p) in newton');
   ylabel('moment in newton-meter');
   hold on;
end
grid on;
```




```
% Angle-Net reactive force relationship for L4/L5 Joint %
close all
clear all
lbes=0.05;%lever arm of erector spinae muscle equivalent
wtr=220;%weight of trunk
lbtr=0.25;%lever arm of C.G of trunk about L4/L5 joint
wa=42.5;%weight of arms in newton
lba=0.3;%lever arm of C.G of arms about L4/L5 joint
p=100;%load in newtons
lbp=0.3;%lever arm of C.G of load about L4/L5 joint
figure ;
grid on;
fes=(wtr*lbtr+wa*lba+p*lbp)/lbes;
for a=0:pi/50:pi/3;
cb=fes+(wtr+wa+p)*cos(a);%compressive force on L4/L5 joint
sb=(wtr+wa+p)*sin(a); %shear force on L4/L5 joint
rb=sqrt((cb)^2+(sb)^2);%net reactive force
xlabel('angle between hand and thorax in radians');
ylabel('net reactive force on L4/L5 joint in newtons');
plot(a,rb,'x');
hold on;
end
```



VI. RESULT

A prediction program was developed to simulate the manual materials handling tasks for investigating the effects of different parameters.

The program was coded in MATLAB which provides users a very rich collection of functions in mathematics, plotting and animation of the results.The model is further used to determine the effect of the size of the load (sagittal half width, 1_2) on the low back reactive forces. Increasing load size (1_2) had a direct effect on the low back reactive force. The relationship was almost linear for both bulky and non-bulky loads. Again, reactive forces at the low back joint were, in general, larger in bulky loads as compared to non-bulky loads. Further, the changes in the low back reactive forces did not occur in the same proportion as in the load size (1_2). A more than 2-fold increase in load size resulted in only an 18% increase in the reactive force at the low back joint for the non-bulky case. For bulky loads, the increase in the magnitude of the reactive force was relatively smaller (about 8%) Optimum configuration of lifting a non-bulky load of variable weight based on minimum low back (L4/L5) reactive force. The other parameter values are:

$h = 0.6$ m,

$l_2 = 0.15$m,

$h_l = 0.45$ m.

Load (N)	α (deg)	δ (deg)	€ (deg)
50	34.4	68.0	64.0
100	34.4	68.0	64.0
150	34.4	68.0	64.0
200	34.4	68.0	64.0
250	34.4	68.0	64.0
300	34.4	68.0	64.0
350	34.4	68.0	64.0
400	34.4	68.0	64.0

Table gives the safe postural configurations obtained by using the cost function based on minimum low back joint (L4/L5) reactive force. The values shown in table are for a non-bulky load with half sagittal width of 0.15 m, and which is grasped at the standing knuckle height (approximately 0.45m). An interesting observation which emerges from table is that the safe postural configurations are independent of the magnitude of the load.

VII. CONCLUSION

A rigid body link model is developed to analysis the symmetric sagittal load lifting in static or quasi-static conditions. One of the major aims of the analysis is to determine how safe working postures will be affected by changes in (i) the magnitude of the load lifted (ii) the load characteristics such as load being bulky or non-bulky, sagittal plane width of load, etc., and (iii) the location of the load in the horizontal and vertical planes.

Biomechanical simulations are carried out using anthropometric characteristics of a typical 50^{th} percentile male person. The model calculations also use the values published in literature for different inputs such as the range of joint movement, involvement of muscles, joint moment strengths, etc., to the model.

In the present paper, an objective function based on minimizing the total low back reactive force has been used to determine safe working postures during load lifting. It has been well established that a large number of workers suffer low back injuries during manual materials handling tasks, especially the load lifting aspect. Therefore, we believe that if mechanical injuries are to be reduced or prevented during lifting tasks, workers should be encouraged to adopt such working postures as would minimize the reactive forces on the low back joint. However, we also think that this should not be done at the cost of other joints that will share the external load. Therefore, the optimization of the reactive force of the low back joint must be obtained subject to the constraint that muscle forces or joint moments do not exceed the maximum values determined for the joint.

These equations consider the effect of gender, percentile population and angles at the joint of interest as well as at an adjacent joint. These equations are incorporated in the computer program to eliminate undesirable postures.

The model predicts a linear relationship between the load lifted and the flexion moment generated at the low back joint. This model response is in complete agreement with the experimentally determined low back flexion moment during a sagittal lift (Schipplein et al., 1990). These authors obtained the moment profile at the low back joint during load lifting and found that the flexion moment at the joint in free style lifting technique increased linearly with load.

The interesting point to note is that the peak flexion moment profile at the joint in the dynamic lifting is similar to the profile obtained by our model which calculated moment values in the static case. This correspondence between the model response and the experimental observation strongly validates the model.

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