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Biomechanical Model of pushing and pulling

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Abstract

This study demonstrates that certain personal and task factors can be modelled to predict slip potential as well as back loadings durings dynamic pushing and pulling tasks. Such tasks are common to many manual material handling jobs in industry and the results of this work will hopefully be of use in improved job design.

The objective of this research is to formulate and validate a dynamic biomechanical model of pushing and pulling a cart. For pushing and pulling tasks, the model can : (1) estimate foot forces for given hand forces, and (2) estimate torso muscle and vertebral column loadings.

In order to formulate and validate the model, experiments involving pushing and pulling of a cart were performed. These experiments produced data of the following type : (1) dynamic forces on the feet, (2) hand forces required to move the cart, (3) body motions as functions of various cart motion and (4) back muscle actions.

The model was validated using three different methods ; precision was tested using correlation between predicted and measured results, accuracy using standard error between of predicted and measured results, and intuitive comparison of predicted results using sensitivity analyses.

1. INTRODUCTION

From the analysis of human motions (using a biomechanical model), every motion can be considered along with the other slip-and-fall factors. However, there have not yet been any slip-and-fall studies that use a biomechanical model.

In a study by Ayoub and McDaniel [1], the capacities of subjects in pushing and pulling against a wall were measured as a function of different body configurations. The study

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also evaluated the load on the lumbar spine during the static pushing and pulling.

Snook etal[4].measured pushing and pulling forces continuously on a modified treadmill powered by the subject. It was found that fifty percent of their industrial male test population could sustain about 264 newtons (27 kg) in 2.1 meters pushing and 216-304 newtons (22-31 kg) in 2.1 meters pulling performed at 30 minutes intervals. Fifty percent of the industrial female test population could sustain 264 newtons and 167-235 newtons (17-24 kg) in the same pushing and pulling situations as described above.

2. DYNAMIC BIOMECHANICAL MODEL

A two-dimensional linkage model is used as a basis for a dynamic biomechanical model to study slip potential and to predict body postures that minimize slip potential for given pushing and pulling postures and forces. The model can also predict back, abdominal muscle and vertebral column loadings under the same circumstances.

The model requires the following inputs:
(1) subject anthropometry-height, weight and link lengths,
(2) body postures during the task (body motion data of joints),
(3) foot contact point (heel or ball of a foot),
(4) cart handle height,
(5) forces exerted on the cart handle (hand forces).

The model, given these inputs, produces the following outputs during one gait cycle:
(1) vertical foot forces,
(2) horizontal foot forces,
(3) an estimation of the minimum coefficient of friction for a given push/pull task required to prevent a foot slip (this estimate is derived from 1 and 2),
(4) back muscle force and abdominal muscle force and vertebral column loading estimates,
(5) estimated reactive force and moment at each joint.

The friction necessary for the subject to maintain balance can be calculated using this force on the foot. To prevent slips, the friction force must be greater than the horizontal force which is produced when a subject pushes or pulls. However, using the maximum coefficient of friction during the double support phase as a reference level may lead to an unnecessarily high level of coefficient of friction since the slip possibility is low in the double support phase. This can be explained by the fact that even if one foot slips, the other foot can support the body and thus prevent slipping. There fore, the instant where maximum coefficient of friction is required during the single support phase may be more hazardous than in the double support phase. This can be a significant consideration since the proportion of the time of double support phase for pushing and pulling was found to be higher than for walking (average 25% of single cycle from anthor's experiments). Therefore, more emphasis was given to the prediction of friction required during the single support phase.

The model used in this study is a revision of The University of Michigan torso model[2] which estimates the compressive force on L_5/S_1 disc. This revision treats the rectus abdominis muscle as one of the force components in the back equation.

3. MODEL VALIDATION

The aspects of the model to be validated are: 1) external foot forces and 2) compression loads at the L_5/S_1 disc. The validation of foot forces was relatively easier than that of compressive forces on L_5/S_1 disc since foot forces could be measured directly using the force platform.

But only in an indirect way the compressive force can be predicted. Therefore, EMG-RMS (Electromyography) was used for estimating muscle force.

Subject

Four male and two female students ranging from twenty to thirty years of age participated in each experiment. There were no subjects with a history of back pain or previous back trauma. Before the experiment, all subjects were informed and instructed about the procedure of the experiments and possible injuries. The link lengths of the subjects were measured before the experiment using the linear-dimension method[3]. Their weight ranged from 50 kgs to 80 kgs and their stature ranged from 162 cm to 175 cm.

Procedure

In this experiment, cart simulator (figure 1) speed, cart simulator counterforce, and height of handle were controlled. Eleven markers (wrist, elbow, shoulder, L_5/S_1, hip, left knee, right knee, left ankle, right ankle, right foot sole and left foot sole) were attached to a subject wearing black leotards for good contrast.

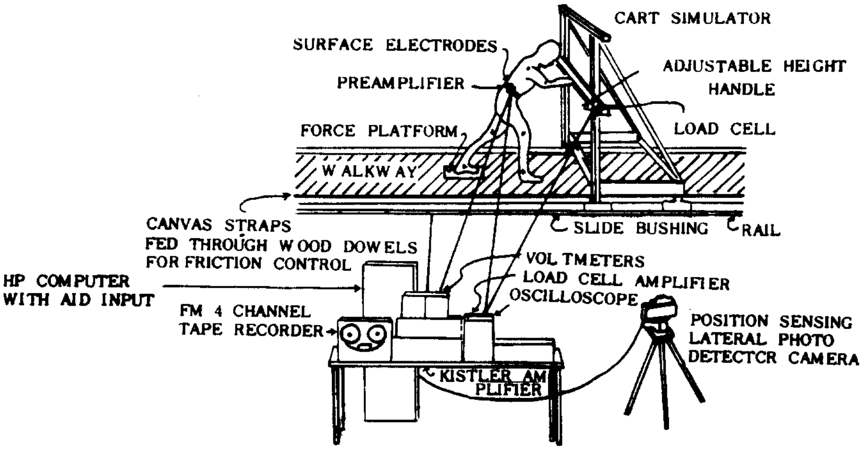

Fig. 1. A Cart Simulator and Instruments For the Dynamic Experiments

RMS of EMG amplitude (EMG_{RMS}) was used to estimate torso muscle activity. The myoelectrical signals were picked up by means of bipolar surface electrodes. Two silver electrodes were placed 3*cm* lateral to the midline on both sides of the spine at the L_2 and L_3 level. Another two silver electrodes are attached on the abdomen 3 centimeters above the umbilicus and 3cm apart from each other. A ground electrode was attached on the ear lobe. The electrode signals were fed to preamplifiers built into a small box, which was strapped to the subject's waist. The signals were further amplified in AC voltmeters, rectified and transferred to the digital computer using an A/D converter. During recording, the signal quality was continuously checked on an oscilloscope screen. This RMS data was used to determine EMG amplitude which provide an estimate of torso muscle activity as the handle force and other variables during pushing or pulling were changed.

For three different handle heights, three different resistive forces were tested and each repeated for pushing and pulling. The subject began the push or pull task at the starting point of the 6*m* track and pushed or pulled the cart simulator the entire length of the track. The computer recorded hand and foot force data at 10 milisecond intervals (sampling rate 100Hz.) while the displacements of the body links was photographed using cameras with a strobe flash at 67 milisecond intervals (i.e. sampling rate 15 Hz). These pictures were analyzed using a digitizer (Graf/Pen) to estimate positions of each link intervals.

The force data were synchronized with the displacement data from the photographs of the landmarks on the subject's body. To prevent this time lag, a special photographic technique employing a flash and a strobe was used. The motion of the subject was taken using the strobe flash which was activated when the experiment started; the flash was activated when the subject's foot touched the force platform .

4. RESULTS AND DISCUSSION

Dynamic Foot Force

Foot forces during pushing or pulling a cart were estimated using the model and were compared to those measured by the force platform. The predicted and measured vertical and horizontal foot forces are compared in Figure 2 showing $r^2 = 0.65$ and .56(significant at $p < .05$) and mean errors of 60 newtons and 19 newtons for vertical and horizontal foot forces respectively.

The peak values of predicted and measured vertical and horizontal foot forces are also compared giving $r^2 = 0.78$ and .61 which is significant at $p < .05$ and mean error of 45 newtons and 14 newtons for vertical and horizontal foot forces respectively.

The ANOVA analysis demonstrated that there is a subject difference effect between peak predicted and measured vertical and horizontal foot forces estimation which is significant at $p < .05$ (average 10 and 8 newtons respectively)

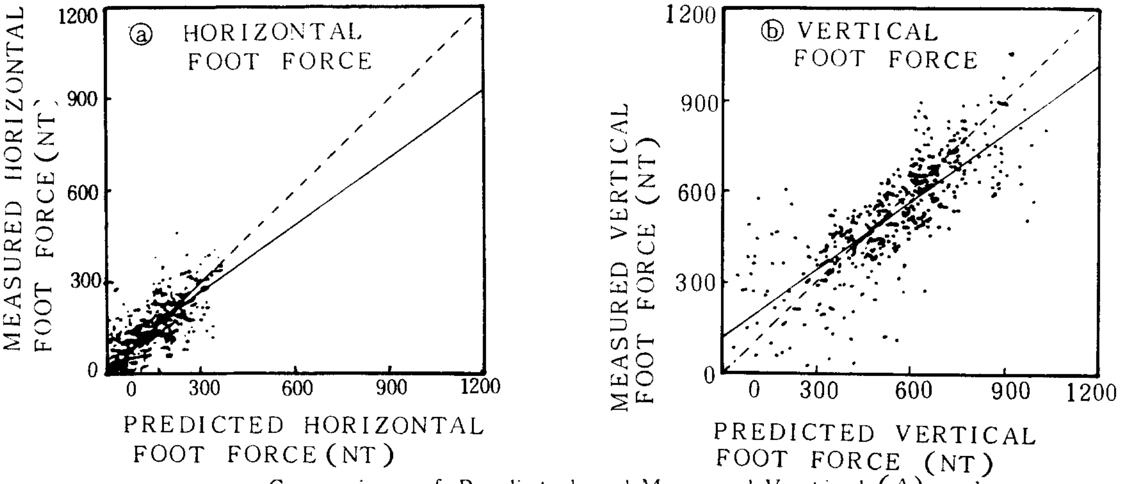

Figure 2 Comparison of Predicted and Measured Vertical (A) and Horizontal (B) Foot Forces of All Experiments (n=791)

Neither handle height effect nor the hand force effect was significant at $p < .05$ level in accounting for differences between the predicted and measured foot forces. There was also no direction of exertion (pushing or pulling) effect in the estimation of horizontal foot forces (Y). However, the direction of exertion indicated a bias in the estimation of vertical foot forces significant at $p < .05$. This effect was responsible for fifteen percent of the total variance. There was a tendency of overpredicting the vertical foot forces by about 60 newtons (approximately 7 lbs.) in pulling and of underpredicting by about 19 newtons (approximately 2 lbs.) in pushing.

Neither direction of exertion (pushing or pulling) nor using the left or right foot had any effect on time lag between the predicted and measured time taken from the start of the gait cycle to the instant of maximum friction .

Muscle Force

To find the $IEMG_{RMS}$ — Isometric Muscle force relationship, three different experiments -- 1) isometric trunk pushing and pulling, 2) isometric hand pushing and pulling in standing erect posture, and 3) isometric hand pushing and pulling in free postures --were performed.

The relationships were derived for each subject using the least square error regression analysis (Linear model) as follows;

$$IEMG_{RMS}\ (\mu v) = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2 + e \qquad (1)$$

where:

x_1 = muscle force of the erector spinae or the rectus abdominis (nt)

x_2 = indicator variable

$x_2 = 0$ if pushing
$\quad\;\; 1$ if pulling

Results of Isometric Pushing and Pulling

In the experiment involving isometric pushing and pulling of the upper trunk where subject's thigh and hip were strapped the rectus abdominis muscle force was active in pushing and inactive in pulling while erector spinae muscle showed opposite results for all subjects. The sample results for a typical subject of the relationship of IEMG$_{RMS}$ with predicted muscle force was linear. Other subject's data showed similar results of linear relationships. Measured IEMG$_{RMS}$ and predicted muscle forces shows good fit (average $r^2 = .93$). These relationships of linearity support the torso model in the biomechanical model for the isometric standing erect condition. Slopes and intercepts were significantly different between erector spinae and rectus abdominis. It was also noticed that the equations vary between subject dependent on positions of electrodes.

Another experiment was performed on an isometric hand pushing and pulling test against the handle which was set at each subject's shoulder height. As was the case in trunk pushing and pulling, the relationship between measured IEMG$_{RMS}$ of muscles and muscle forces was linear. IEMG$_{RMS}$ also fit well (average $r^2 = .96$). The same variation as trunk pushing and pulling showed between and within subject. However, these relationships of linearity and good fit also support the torso model in the biomechanical model for the isometric hand pushing and pulling in standing erect position.

The IEMG $_{RMS}$ of the erector spinae muscle predicted by the model showed relatively low correlation ($r^2=0.31$) but significant at $p \leqq .05$ with IEMG$_{RMS}$ measured during the dynamic experiments. The predicted IEMG $_{RMS}$ of rectus abdominis muscle also showed relatively low correlation with IEMG $_{RMS}$ ($r^2=0.44$) which is significant at $p \leqq .05$.

In conclusion, the torso model predicts the muscle forces in the isometric hand pushing and pulling --hand experiments -- in a standing erect posture ($r^2 = .96$ and within ± 3% of prediction error for 95% confidence limit) and in a free postures ($r^2 = .31$ and .44 respectively and ± 15% of prediction error). While the correlation "r^2's" are lower in the dynamic case than in the isometric case, the model still provides the means to conservatively estimate dynamic muscle forces. This is significant in light of the fact that the dynamic case produces much more signal noise than the isometric case.

Comparison of Static and Dynamic Models

The moments and forces acting at various joints were predicted using static and dynamic biomechanical models for typical conditions and subjects. Since the static predictions were done using the same time step motion data used in the dynamic predictions, the inertia effect could thus be found. Prediction of low handle pushing which is one of the tasks requiring a high coefficient of friction Therefore, this task was used for comparison of static and dynamic effects using subjects 2 (female) and 5 (male), who are quite dissimilar in heigt and weight.

There was a big difference in the compressive force and the coefficient of friction between subiects for almost the same hand force. This was due to differences in the anthropometry (weight and height) .

The result shows that the moments increase rapidly as the velocity increases. However, the result of slow speed pushing (1.8 ㎞/h) was not much different from the static predictions. This implies that the static prediction may be reasonable for the analysis of a task in which a person is working near maximal strength and thus must move slowly. It can be seen that there is high probability of injury if someone moves fast even where light objects are handled.

References

〔1〕 Ayoub, M. and J. McDaniel "Effects of Operators Stance on Pushing and Pulling Tasks ," *AIIE Transactions*, Vol 6, No.3, pp. 185-195, September, 1974.

〔2〕 Chaffin, D.B. " Low-Back Stresses During Load Lifting," Technical Report, The University of Michigan, 1973.

〔3〕 Roebuck, J.A., K.H.E. Kroemer and W.G. Thompson *Engineering. Anthropometry Methods*. John Wiley and Sons , New York, 1975.

〔4〕 Snook, S.H., C.H. Irvine and S.F. Bass " Maximum Weights and Workloads Acceptable to Male Industrial Workers While Performing Lifting, Lowering, Pushing, pulling, Carrying and Walking Tasks," ***Proc. American Industrial Hygiene Conference,*** Denver ,Colorado May, 1969.