Toward Electronic Work Design

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ABSTRACT

The dynamic behavior of a musculoskeletal link system in manual lifting is simulated by a mathematical model which contains a non-linear objective function and a set of linear, as well as non-linear constraints. The model was developed based upon the hypothesis that an individual performs the lifting motion following the principle of minimizing mechanical work done. The simulation model demonstrated that the associated differences between the predicted motion and the measured motion is biomechanically feasible and the accuracy is adequate enough with an average U statistics ranging from 0.012 to 0.209.

INTRODUCTION

Static and dynamic biomechanical lifting models exist. The static models, neglecting the dynamic effects of acceleration and momentum, are reported to underestimate the stresses. The current dynamic models, on the other hand, lack the data on dynamic muscular strength and on acceptable limits for compressive forces, and therefore have limited practical values (Garg, et al., 1982). The objective of this study is to develop a dynamic lifting model which provides a lifting profile with the associated biomechanical loads at each joint within the dynamic strength limits.

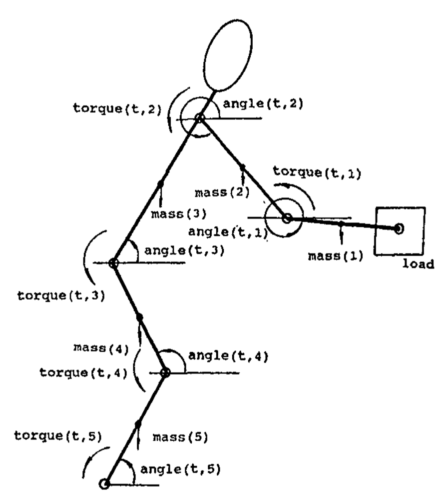
This study used a mathematical programming approach to simulate and evaluate lifting tasks to avoid the need for human motion tracking experiments, data collection, and data analysis procedures. The model was developed based upon the hypothesis that human lifting pattern follows the principle of minimizing mechanical work, while maximizing the utilization of the musculoskeletal system. The input data of the model includes (1) anthropometric parameters of the individual, (2) characteristics of the container (size, weight), (3) initial and final position angles of five major joints, and (4) the task performance time. The output data includes the time history of the five joint angles and the time history of five joint moments. The trajectory is such that it minimizes the mechanical work done while maximizing the utilization of all joints and remaining within the feasible region of the proposed constraints.

MODEL FORMULATION

Model Assumptions

The human body is represented by five rigid links with seven degrees of freedom in the Cartesian Coordinate system. Figure 1 illustrate the link system. The links are pin-centered at the joints such that the moment arms are constants throughout the motion. The density and the shape of the segment remain uniform throughout the lifting motion; the center of mass of each link maintains its location with respect to the proximal and distal joints. The radius of gyration remains constant during the motion and the load does not contribute to the determination of radius of gyration of the wrist. Passive moments created by the passive structure spanning the joints were considered insignificant in the formation of forces and moments at joints.

Figure 1: The Five Link Human Model



Objective Function

The objective function is the minimization of the time integral of the sum of the square of the active state of each joint (a modification from Pedotti, et al., 1978). This is the summation over time of the sum of the square of the ratio of predicted joint moments to the corresponding joint strengths generated under steady state maximum exertion. The summation of moments at each joint is proportional to the amount of mechanical work and was justified to be an index of injury rate (Muth et al., 1976). The "square" term provides for a heavier penalty for large deviation (compared to linear) in the minimization process.

Mathematical Model Development

To describe the mathematical simulation model of lifting, we first define the following terms: angle(t,1), angle(t,2), ..., and angle(t,5) are joint angle measurements at time t of the elbow, shoulder, hip, knee, and ankle, respectively. Torque(t,1), torque(t,2), ..., and torque(t,5) are muscle moments at the elbow, shoulder, hip, knee, and ankle at time t, respectively. The mathematical relationships between joint angles and torques are specified in (Lee, 1988). The mathematical form of the objective function and constraints are:

I. Objective Functions:

$$\text{opt\_obj} = \text{Min} \int_0^T \sum_{j=1}^{5} \left(\frac{\text{torque}(t,j)}{\text{max\_stren}(j)} \right)^2 dt \quad (1)$$

II. Nominal Constraint Set:

$$\text{angle}(0,t) = a(j),\ \text{angle}(T,j) = b(j) \quad (2)$$

$$\text{ang\_lb}(j) \leq \text{angle}(t,j) \leq \text{ang\_ub}(j) \quad (3)$$

$$\sum_{j=1}^{5} (\text{seg\_len}(j) \times \cos(\text{angle}(t,j))) \geq \text{reach\_x} \quad (4)$$

$$\text{box\_x}(t) \leq \text{edge\_x if box\_y}(t) \leq \text{edge\_y} \quad (5)$$

$$\text{acc\_lb}(j) \leq \text{acc\_ang}(t,j) \leq \text{acc\_ub}(j) \quad (6)$$

$$\text{del\_acc\_lb}(j) \leq \text{del\_acc\_ang}(t,j) \leq \text{del\_acc\_ub}(j) \quad (7)$$

$$\text{torque}(t,j) \leq \text{max\_stren}(j) \quad (8)$$

$$\sum_{j=1}^{5} \text{mass}(j) \times \text{cg\_x}(t,j) / (\text{load}+\text{weight}) \leq \text{cg\_sys\_x}(t) \quad (9)$$

where:

opt_obj: the objective function,
max_stren(j): maximum joint strength,
a(j): the initial jth angle,
b(j): the final jth angle,
ang_ub(j) and ang_lb(j): the upper and lower bounds of jth joint angle,
seg_len(j): the jth segment length,
reach_x: the arm reach in the x_axis,
box_x(t) and box_y(t): the coordinates of the box,
edge_x and edge_y: the coordinates of the edge of the workstation,
acc_ub(j) and acc_lb(j): the upper and lower bounds of jth joint angular acceleration,
del_acc_ang(j): the upper bound of the rate of change of angular acceleration,
mass(j): the jth segment mass
load: the box weight
weight: the body weight
cg_x(j): the center of gravity of jth segment in the x_axis,
cg_sys(j): the center of gravity of the system in the x_axis,

To facilitate the integration computation, the continuous time integral was decomposed into a set of discrete epochs and the integration operation replaced with summation. In this discrete process, the time parameter manifested itself in the form of the number of stages, k, in the process, that is:

$$T = \text{n\_stage} \times \text{delta\_t}, \quad (10)$$
$$0 \leq k \leq \text{n\_stage, and } t = k \times \text{delta\_t}$$

To simplify the model, the location of joints was written equivalently in terms of the joint angles and segment lengths:

$$x(k,j) = x(k,j-1) + \text{seg\_len}(j) \times \cos(\text{angle}(k,j)) \quad (11)$$
$$y(k,j) = y(k,j-1) + \text{seg\_len}(j) \times \sin(\text{angle}(k,j))$$

The differential equation were approximated by difference equations, for example:

$$\text{acc\_ang}(k,j) = (\text{angle}(k-2,j) - 2 \times \text{angle}(k-1,j) + \text{angle}(k,j)) / \text{delta\_t}^2 \quad (12)$$

The physical system is characterized at each stage, k, by a set of state variables, angle(k,j), describing the movement profiles of each joint. At each stage, the state variables are selected from the feasible region of the time-variant and constrained state space. The effect of this decision at stage k is a transformation of the state variable at stage k-1 to stage k. The performance measure is approximated by

$$\text{opt\_obj(n\_stage)} = \text{Min} \sum_{k=1}^{\text{n\_stage}} \sum_{j=1}^{5} \left(\left(\text{torque(angle(k-2,j),angle(k-1,j),angle(k,j))/max\_stren(j)}\right)\right)^2 \quad (13)$$

The approximation of this performance measure is a function of the vector (angle(1,1) angle(1,2) angle(1,3) ... angle(n_stage,5)) with 0<k<n_stage. There are 5x(n_stage) variables in the objective function. The resulting problem is to find the 5x(n_stage) joints angles that minimize the objective function and satisfy the joint angular difference equations and bounds. The problem was solved using the "Trajectory Approximation in State Spaces" method (Durling, 1964) developed in association with a search technique. The search is carried out on a 20-stage lifting process, with 5 state variables in each stage. Dynamic programming is used to identify, throughout the lifting process, the optimal joint position angles.

Procedure

This research project consisted of three activities. The first effort was to identify lifting joint displacement and time relationships, and to generate a time variant joint-strength data base. All the bound values of the constraint set were obtained in this phase of research. The second effort was to mathematically develop the optimization model. Finally, the mathematical model was evaluated by the lifting kinematics and kinetics data.

Four trained subjects participated in the experiment to obtain the lifting kinematics data. Anthropometric measurements were obtained for each subject and were used as model inputs. Adhesive markers were attached to subject's six joint centers (wrist, elbow, shoulder, hip, knee, and ankle). The subject performed the lifts using a pre-determined box size and lifting range. The subject determined their one time maximum acceptable weight of lift (MAWL) using the psychophysical approach (Ayoub, et al., 1984) under each set of task conditions. Four lifts were recorded using the MAWL for each task. Motion recording was accomplished using the motion analysis system of ExpertVision. Recordings were made for each subject performing simulated lifting task I (lifting from floor to knuckle height) and II (lifting from floor to shoulder height). Joint strength values for five joints were measured using a Cybex II Isokinetic Dynamometer. The maximum joint strength capacities were used as the upper bound to joint strength, at the corresponding moving speed, in the optimization process.

To evaluate the model, the predicted lifting joint trajectories were compared to the measured data subject to different task conditions. Theil's coefficient of inequality (Dennis, 1984) was used to evaluate prediction accuracy.

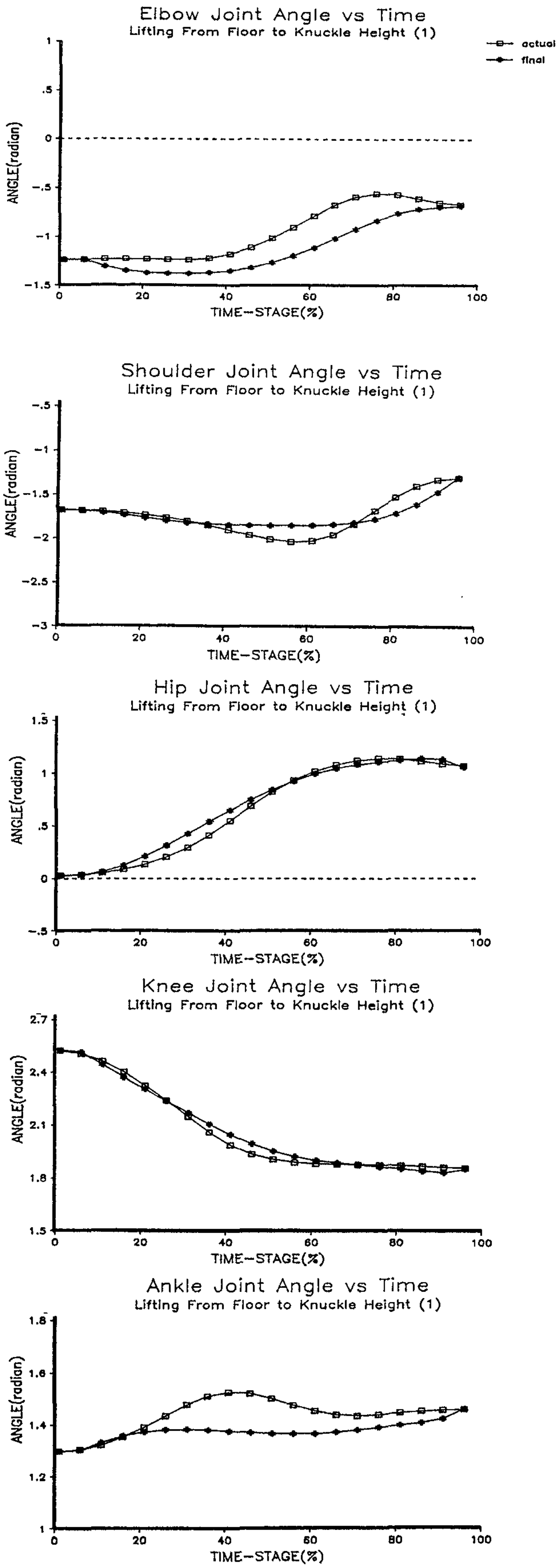
MODEL APPLICATIONS AND EVALUATIONS

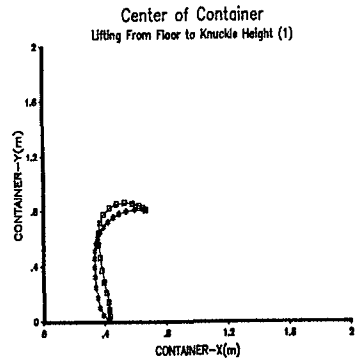
Model Applications

The two lifting tasks were simulated using the simulation model: example 1 dealt with lifting from floor to knuckle height and example 2 dealt with lifting from floor to shoulder height. Due to space limitation the results of only one example will be shown. two sets of trajectories are presented to illustrate the behavior of hand, elbow, shoulder, hip, knee, and ankle joints. Figures 2 illustrates the comparisons. The first set is an 'actual' lifting motion, the second set is the 'final' trajectory (the last trajectory before the optimization process was stopped). In this example, the optimization process was stopped after 46 iterations.

To better understand the model predicted lifting trajectories, refer to the resultant moments at the joints. The moment histories at joints, as functions of the predicted trajectories, justify the soundness of the model which allocates most of the load to the strong joints, especially the lower extremity joints (knee and ankle). Figure 3 provides the comparisons of the maximum moment at the joints of example problem 1. In the actual case, the maximum joint moments were 116, 118, 89, 313, and 205 newton-meters at both elbow joints, both shoulder joints, both hip joints, both knee joints, and both ankle joints, respectively. They occurred at 95%, 70%, 95%, 15%, and 20% of the lift time, respectively. In the predicted case, the maximum moments were 84, 102, 84, 382, and 273 newton-meters at both elbow joints, both shoulder joints, both hip joints, both knee joints, and

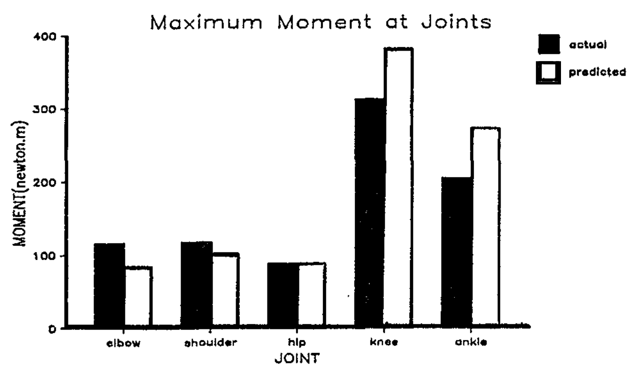
Figure 2: Comparing Model Predictions vs. Measured Joint Trajectories





both ankle joints, respectively. They occurred at 85%, 80%, 80%, 15%, and 15% of the lift time, respectively. In general, the maximum moments at the joints were in phase for the cases of actual lift and the predicted lift. There was substantial relief of the load on the elbow and shoulder joint (savings of 32 and 16 newton-meters) and the load was distributed to the knee and ankle joint where an extra 69 and 68 newton-meters were generated, respectively. The savings of mechanical load at the elbow and the shoulder joints resulted from limiting the flexion of elbow joints and the delay extension of the shoulder joint. As a result, more loads were allocated to the lower extremity joints.

Figure 3: Comparing the Predicted vs. Actual Maximum Moments



Model Evaluations

Accuracy analysis of the model predictions was conducted based on Theil's coefficient of inequality. Table 1 reports the accuracy analysis of the example problem.

Judging by the modest size of the U statistic, the accuracy of the model is considered adequate. The inequality coefficient U values are 0.209, 0.069, 0.085, 0.012, and 0.057 for the prediction of elbow, shoulder, hip, knee, and ankle joint behavior, respectively. The success of the

Table 1
Accuracy Analysis of The Example Problem

joint	U-statistic	UM	UR	UD	r
elbow	0.209	0.699	0.009	0.292	0.91*
shoulder	0.069	0.008	0.120	0.872	0.86*
hip	0.085	0.345	0.004	0.651	0.99*
knee	0.012	0.002	0.000	0.998	0.99*
ankle	0.057	0.557	0.000	0.443	0.56*

U:Theil's inequality coefficient
UM:the prediction error due to bias
UR:the prediction error due to regression
UD:the prediction error due to residual
*:statistically significant at alpha=.05

predictions can also be supported by the high and statistically significant correlation, r, between the predicted and the measured joint behavior. The decomposition of the mean square error (UM, UR, and UD) indicates the evidence of systematic error due to bias (the UM values ranging from 0.002 to 0.699), namely, underestimation of the average joint angles. However, based on the fact that the slope of the relationship between the actual and its predicted series (the UR values ranging from 0.000 to 0.012) does not differ significantly from 0, and the non-systematic error (random disturbance), UD (the UD values ranging from 0.292 to 0.998) constitutes the majority of the mean square error. The quality of the predictions was justified.

CONCLUSIONS

To interpret the results, it is important to consider the validity and sensitivity of the model. Regarding this:

(1) Smooth as well as ballistic motion was predicted.

(2) The predicted joint trajectories are matched, in trend, with the measured joint trajectories. This indicates that joint moments are at least functionally involved in determining the lifting profile.

(3) The disagreements between the actual and predicted lifting profiles can be largely explained by the differences between the input physical constraints to the model and the individually perceived constraints.

(4) Comparing the predicted motion profile to the actual one, the optimizing routine predicted a motion pattern where more load was allocated to the lower extremity joints in the initial phase of lifting. The upper extremity joints (elbow and shoulder), relatively weaker than the lower extremity joints, did not become actively involved in the motion until the completion of the container was taken off the floor.

(5) The simulation study, which paid particular attention to the mechanical behavior of the link system in lifting tasks, demonstrated that the associated differences between the predicted motion and the measured motion is biomechanically feasible and the accuracy is considered adequate with an average U statistics ranging from 0.012 to 0.209.

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