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PREDICTING THE OPTIMAL LIFTING MOTION THROUGH SIMULATION

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Biomechanical analyses and models serve a useful purpose in estimating the stresses on the musculoskeletal system. In dynamic biomechanical analysis, displacement-time data must be known in order to estimate the kinematics and kinetics of the movement. However, the collection of this displacement data is both tedious and expensive. With the development of simulation lifting models, it is possible to provide an indirect means of performing the biomechanical analysis without having to actually collect the displacement-time information. The significance of the current research is its ability to estimate the kinematics and kinetics of lifting movements under specified characteristics of the anthropometry, the work station, and the lifting task.

MODEL SPECIFICATION

In the study of models to predict optimal lifting motions, displacement and time relationships can be estimated at various joints of the human body using optimization techniques. It is assumed that the lifting motion performed by the body will be chosen in order to minimize some cost function. The cost function selected for this study hypothesizes that while lifting, the body will minimize the effort it needs to exert, subject to various constraints related to the capability of the body, the physical layout of the task, and those pertaining to the kinematics and kinetics of the motion.

In recent studies by Lee (1988) and Ayoub, et al., (1992, 1991, 1990, 1989), a simulation model utilizing five select joints, the elbow, shoulder, hip, knee and ankle, was developed for sagittal lifting activities. It is hypothesized that the lifting trajectory will be performed so as to minimize the following objective function:

$$Minimize\ f = \int_0^T [\sum_{j=1}^5 w_j (\frac{\tau_j(t)}{M_j(t)})^2] dt$$

where w_j are the weighting factors, currently set to a value of one, $\tau_j(t)$ for $j = 1,2,...,5$ are the joint moments at time t, and $M_j(t)$ for $j = 1,2,...,5$ are the maximal moments at time t based on the joint strength generated under steady state maximum exertion by Stobbe (1982) and Chaffin and Anderson (1984). This modelled objective function uses a ratio of $\tau_j(t)$ to $M_j(t)$ to emphasize that the optimization process distributes moments to the joints according to their relative capacities. The "square" of the ratio provides a heavier penalty for any deviants from the optimum. The weighting factors are used to adjust the contribution to the objective function from each of the five joints. The objective function in use in this model is a modification from Pedotti et al., (1978); however other objective functions such as power or the total work performed may prove to be better predictors, thus require examination.

The biomechanical model makes the common assumptions that the body can be represented as five rigid links with pin-centered joints and the density and shape of the segments remain uniform, thus the configuration of the body can be described in terms of joint angles and link lengths. Additional assumptions related to task performance include: the lifting begins from a stationary posture with no movement before the beginning of the lift; the container is within the subject's reach envelope at the beginning and end of the lift; the lift is symmetrical and motion occurs only in the sagittal plane; and the subject neither walks with the load nor throws the load, instead the load is smoothly lowered to its end position.

The objective function is subject to the following set of constraints (g_j):

(1) Constraints related to the human body: The range of motion of each joint is bounded by a minimum angle and a maximum angle and all feasible joint motion is restricted within these boundaries.

(2) Constraints related to the physical layout: The path of the load's container must avoid collisions with the edge of the workstation, the tibia, the knee, and the abdomen. Also the combined center of gravity of the human body and container must remain within the range of the lifter's foot.

(3) Kinematic constraints: The angular velocity, angular acceleration, and the rate of change of angular acceleration of the five joints are constrained by upper and lower bounds to ensure the that the lifting path generated by the model is a smooth path.

(4) Kinetic constraints: The resultant torques at the joints produced by the forces on the joints, body segment weights and any external forces are bounded by the maximum voluntary torque that the joint is capable of producing.

MODEL APPLICATION

The model, with its quadratic objective function and both linear and non-linear constraints, requires the minimization of a time integral of a function. Hsiang (1992) selected the Generalized Reduced Gradient (GRG) algorithm to solve the optimization problem. The GRG algorithm is a finite improvement algorithm which is used to solve nonlinear optimization problems with bound constraints. It begins with the assumption that $\theta_j(t)$, the angular displacement is a differentiable function, such as a polynomial. Thus, the cost function f and the constraints set g_i become functions of polynomials. This method searches the response surface $L(f, g_1, g_2, ...)$ constructed by f and the constraints set g_i, and the gradient of the response surface is used to determine the direction for minimizing f. If coefficients of the polynomial are found to minimize the cost function f, the optimal motion pattern is found.

In order to study the model's performance, a validation process was performed. Four subjects lifted four repetitions of their maximal loads under four conditions (two ranges of lift X two container sizes.) The inputs to the model were: (1) the initial and final positions of the load, (2) the time to perform the lift, (3) the height and weight of the subject, (4) the weight of the load, (5) the geometric dimensions of the workstation and the container, and (6) the physical constraints regarding the range of motion, reach envelop, center of mass, acceleration, and the first derivative of the acceleration.

To validate the model, the displacement-time data predicted by the model was compared to the subjects' actual patterns. Two statistical methods were used to perform the comparison: (1) the sum of squares, which is a measure of the geometric distance between the predicted and the actual data; and (2) the number of pairs of disconcordance, which is a measurement of the trend between the predicted and actual displacement-time data. The smaller the value of the sum of squares and the fewer the number of disconcordant pairs, the better the model. Graphical comparisons were also made between the model predictions and the actual motion patterns performed by the subjects. (Figures 1 and 2).
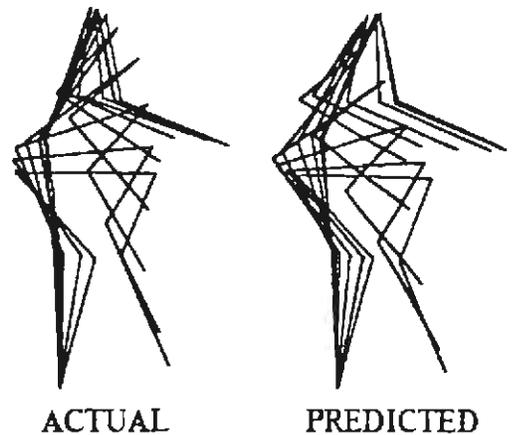

ACTUAL   PREDICTED

Figure 1. Actual versus predicted total lifting pattern.

In general, the pattern formed by the four repetitions of the actual data is usually overlapped with the envelope constructed by the predictions. Although there are variations from trial to trial, the motion patterns are basically close to each other and follow a similar trend. However, consistent experimental discrepancies were observed including: (1) Plots of the angular displacements of the knee and ankle joints show that subjects tend to quickly straighten their legs at the beginning of the lift, then use their trunk and upper extremities to complete the lift. However, the model shows this motion to be disadvantageous since it increases the value of the
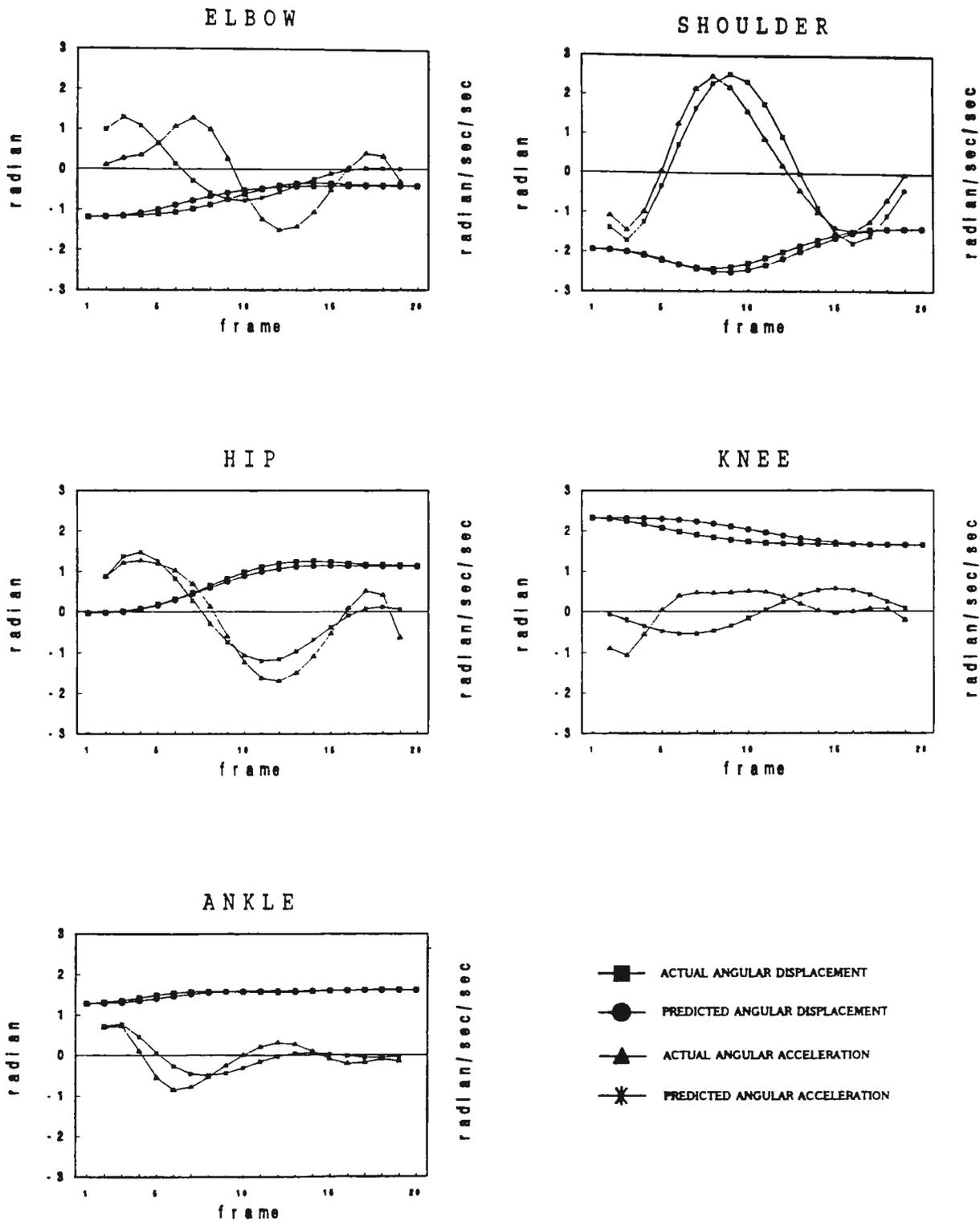
Figure 2. Actual versus predicted angular displacement and acceleration for five select joints.

objective function. (2) The graphical comparison showed that the subjects tended to move the load close to their bodies at the beginning of the lift; however, the extra load travel is not predicted by the model since it may increase the objective function. (3) Through comparison, the shoulder joint was found to be less well predicted than the other four joints. This result may be due to the upper arms abduction. adduction and rotation, as well as the assumption that the spine can be modellled as a single link.

FUTURE INVESTIGATIONS

Although the model has generally proven to be a good predictor, the discrepancies noted above require investigation. In addition to expanding the scope of the model to predict more ranges of lift, container sizes, and subjects, research activities planned to further advance the development of the model, as well as address the discrepancies, include:

(1) Phase relationships, a phase shift in time in the predicted motion with respect to the actual motion, were found. In the actual motion, some joints move slightly before others, and sometimes even before the container is lifted off the ground. Thus some model error may be the result of ignoring the initial joint movements prior to liftoff of the load. Incorporation of phase relationships and joint coordination may improve the model.

(2) One of the basic assumptions used in the model and which contributes to the simulation error was that the trunk is one rigid link. By modelling the trunk as two or more links, the prediction accuracy should improve. To model this, an attempt in which the spinal links are assumed to be auto-correlated has been made. Given the coordinates of the first and last link, the shape of the spine can be estimated. This spinal model will be incorporated into the simulation model.

(3) Danz (1991) found that shortly prior to the liftoff of the load, the hands applied a relatively large force to overcome the inertia of the load. The incorporation of this pre-liftoff initial force into the model may improve the simulation.

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