

Biomechanics of manual material handling through simulation

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ABSTRACT

In ergonomics, biomechanical models are used to analyze stresses imposed on the musculoskeletal system. To conduct dynamic analyses, data regarding the motion of the body must be collected. If successfully developed, motion simulation can be used in place of the collection of joint coordinate data. A two-dimensional whole-body lifting simulation model is presented in this paper. Using an optimization concept, manual lifting motion is generated to satisfy an objective function subject to various constraints including limitations in kinetics and kinematics and those imposed by the physical layout of the task. Examples on the formulation of the constraints are given. Results of the simulation indicate that it is possible to improve the predicted motion by incorporating more realistic constraints provided that a reliable mathematical optimizer is available.

INTRODUCTION

Computerized human motion synthesis has generated interest in many scientists and engineers due to the fast advances in computer technology and the need in areas such as computer animation, biomechanics, orthopedics, rehabilitation, bioengineering, ergonomics, etc. There is a need in these areas to predict the behavior of the human body movement under environments or conditions in which actual experiments are difficult or impossible to conduct. Early simulation modeling efforts were usually restricted to a single or few segments such as the upper or lower extremities with limited degrees of freedom in motion (Townsend and Scireg, 1972). More recently, whole body and three-dimensional modeling allowing more degrees of freedom became successful (Yamaguchi 1990, Hatze 1981).

In ergonomics, biomechanical studies of manual lifting represent a major area of interest. To estimate stresses imposed on the body's musculoskeletal system while lifting, especially forces at major joints and the lumbar spine, two or three-dimensional whole-body dynamic models are used. The requirement in using these dynamic models is that the motion of the body must be recorded when the task is performed. The motion acquisition often requires expensive motion analysis systems using computer work stations.

It is the purpose of this study to develop a simulation model which can be used to accurately simulate lifting motions, to eliminate the need for data collection, and to provide predictive power to traditional biomechanical analysis in the ergonomics of manual material handling. This paper describes the lifting simulation model currently under development and demonstrates how this model can be used to predict the behavior of movement without having to conduct actual experiments and answer various what-if questions.

MODEL DESCRIPTION

The approach proposed by Hsiang (1992) and Lee (1988) in simulating human lifting motion is followed. In this approach, a basic assumption is used: the human body performs a motion, particularly in high exertion tasks, according to some internal criterion such as the minimization of total muscular effort. The task under simulation is a symmetrical lift in the sagittal plane. The body is considered as 5 rigid links. The 5 rigid links perform motions in the sagittal plane and each link makes a rotational angle with the horizontal. The system under consideration thus has 5 degrees of freedom, namely, 5 rotational angles which are used to describe the configuration of the body. The inertial property of each body segment was taken from the literature as compiled in Winter (1990). Equations of motion can be derived either by Newtonian or Lagrangian method. Using optimization concepts, lifting is assumed to be performed in such a way that it minimizes the objective function:

$$\text{minimize } \int_{t=0}^T \sum_{r=1}^5 \left(\frac{M_r(t)}{S_r(t)} \right)^2 dt$$

where S_j is the moment strength of each joint,
 M_j is the reactive moment at each joint,
and T is the time to perform the lift.

The ratio of the joint moment to strength represents the muscular effort exerted at that joint. The summation of the squared ratio over the 5 joints under consideration represents the total muscular effort of the body at one moment in time during the lift. By minimizing the time integral of the total muscular effort over the entire period of the lift, the solution is ensured to depend on the complete history of the specified task.

The constraints under consideration are categorized into four classes: kinematic constraints, kinetic constraints, physical layout constraints, and other constraints. Kinematic constraints specify the upper and lower bounds of displacement, velocity, acceleration, and jerk for the joint angles. Kinetic constraints specify upper bounds of the joint moment strength. Physical layout constraints specify the bounds on the geometric relationships between the subject, the table, and the load. Other constraints specify the movement relationships between the joints and the center of gravity of the system.

The inputs to the model include subject height and weight, total lifting time, weight of the load, and initial and final postural configurations of the body (represented by the 5 joint angles). The outputs from the model are the time history of the angles of the 5 joints.

CONSTRAINTS FORMULATION

In optimization theory, the objective function may be thought of as the cost function of the system and the constraints the available resources of the system. While the cost is being minimized, the resources are usually limited. The constraints are used to control the amount of resources available to the system. Numerically, constraints serve to reduce the feasible solution space while searching for the optimal answer. The current approach in using optimization to model the lifting task allows the manipulation of the constraints to find better motion prediction provided that a reliable numerical algorithm is available. The mathematical formulation of the constraints are described as follows.

Kinematic Constraints

Kinematic constraints specify boundary limits for the kinematics of the joint angles. They have a form where angular displacement, velocity, and acceleration are within upper and lower limits.

The bounds on the angular kinematics of each joint are used to restrict the motion according to the normal range of motion kinematics.

Kinetic Constraints

Kinetic constraints specify the boundary limits for the joint moments. They have the form:

$$M(t) \leq S(t)$$

where $M(t)$ is the reactive moment of each joint at time t ,
and $S(t)$ is the moment strength of each joint at time t .

The constraints on joint moments describe the strength-limited behavior of the human motion. Since the current lifting simulation is modeled within the gross musculoskeletal level, the joint moments are assumed to represent the total muscular effort exerted by muscles crossing the joint. This assumption greatly simplifies the model and has the advantage of avoiding the need to model the intricate internal dynamics of the neural and muscular systems.

Physical Constraints

There are two physical layout constraints which specify the geometric relationships of the subject, box, and table. The first one describes the box-table collision avoidance and the second one describes the box-knee collision avoidance. These two constraints describe the collision avoidance of the motion. Figure 1 shows the geometric relationships between the subject, the box, and the table. The final position of the center of the box is known. The horizontal position of the front edge of the table is estimated. The

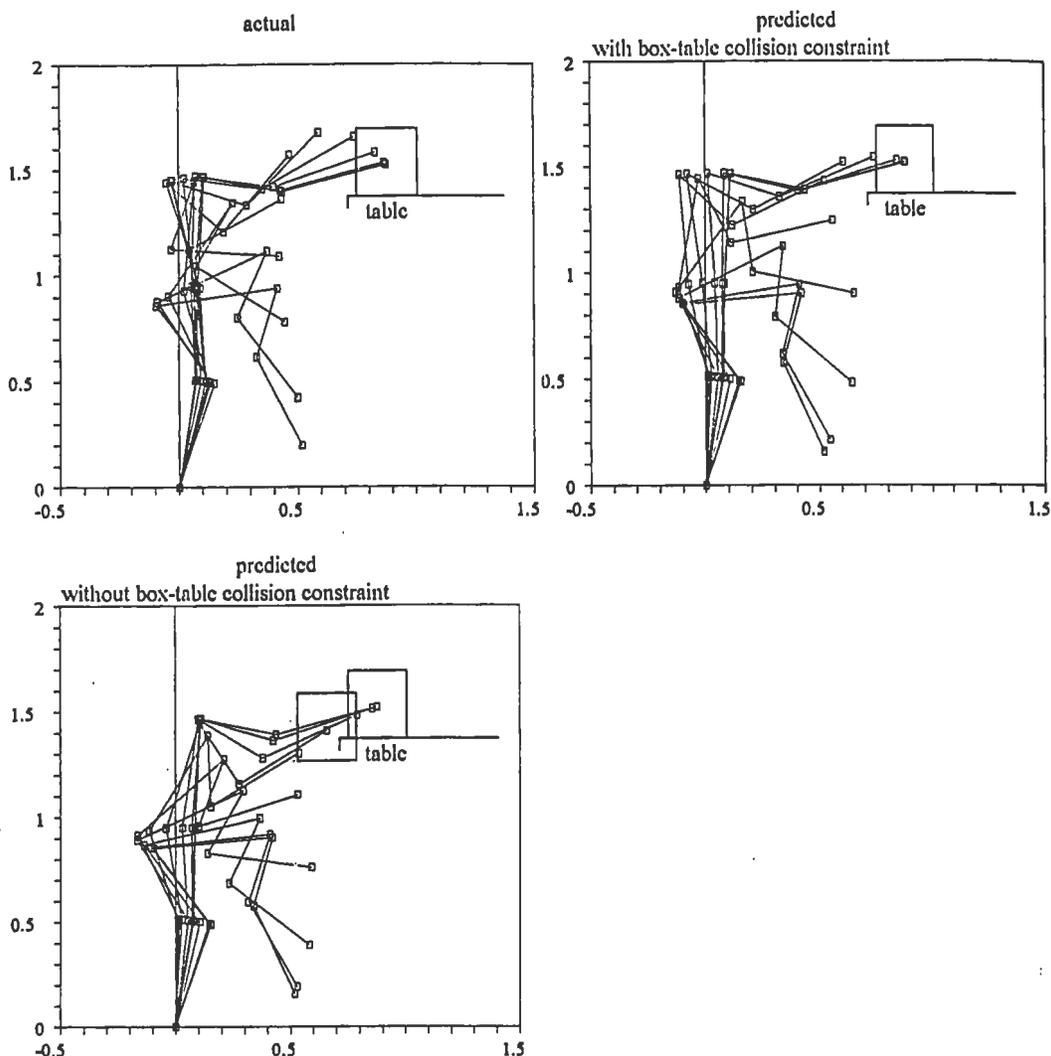


Figure 1. Stick Diagrams of the actual and the predicted (with and without box-table collision constraint) lifts.

vertical height of the table is estimated. When there is nothing under the table, the box may go under the table during the lift; however, when the box is near the surface of the table, the subject refrains from hitting the table. The first constraint indicates that when the center of box is at a height within a certain tolerance δ and the front edge of the box cannot move beyond the edge of the table in order to avoid collision.

SOME RESULTS ON THE ANALYSIS OF CONSTRAINTS

Although the concept of modeling lifting motion as an optimization problem appears simple, the implementation requires considerable numerical effort. The model has a non-linear objective function subject to various non-linear constraints. The computation process from the angular position to any of the terms in the objective function or constraints is also a non-linear transformation. The complexity of the model makes the selection of the numerical algorithm critical for obtaining a solution. Currently, the Generalized Reduced Gradient algorithm developed by Lasdon and Waren (1979) is used. For a detailed discussion of the solution methods, the reader is referred to Ayoub and Hsiang (1992). As an example of how the constraints may affect the solution, the effects of the box-table collision constraint on the predicted motion is illustrated in Figure 1.

The subject under simulation had a height of 1.8 m and a weight of 96.8 kg. The task was to lift a load of 8.86 kg from the floor to the table at his shoulder height (1.37m). The lift took 2.6 seconds to complete. Initial and final postures and other relevant information were used as inputs into the model. The model was used first without enforcing the box-table collision constraint while all other constraints remained in effect in the model. The model was then used with the box-table collision constraint and all others in effect. Figure 1 shows the stick diagrams resulting from the actual lift, the predicted lift without the box-table collision constraint, and that with the box-table collision constraint. It is apparent that both the actual lift and the predicted lift with the box-table collision constraint had a box trajectory curving around the table. The box was lifted up and lowered down onto the table. The predicted lift without the table constraint failed to have this object-avoidance motion. The box went through the table, directly to the final resting position on the table. Furthermore, with the use of the table constraint, the predicted motion showed a faster pull-off at the beginning of the lift similar to the actual lift.

DISCUSSION

As illustrated in the box-table collision avoidance constraint, the simulation model is capable of analyzing various questions without having to carry out actual experiments. In this example, the question being asked was: What would the optimal motion of the subject and the trajectory of the box be if there was no table? Other questions regarding the ergonomics of the task can be asked similarly. If the table is higher or farther away, will the subject be able to complete the lift and what kind of motion will it require? Is it going to be more stressful? Questions regarding the biomechanics of the movement can also be analyzed. How would the motion change if the strength of the knee joint was reduced because of an injury? Such questions are quite difficult to answer if the traditional biomechanical approach is used to investigate the problem. With the aid of lifting simulation models, such questions can be potentially investigated. It must be noted that although the simulation has predictive power, the interpretation of results must be done carefully since there are assumptions and hypotheses built into the model.

Another interesting point is that by comparing the differences between the actual and predicted motions, one sometimes gains insights into parameters that may have been ignored in the model. For example, it is noticed that the actual lifts are usually faster in the beginning of the lift. The optimal motion predicted by the simulation model is, however, much slower at this stage of the lift. Does this imply that the actual lift should be slowed down to optimize the total muscular effort or that there is some important criterion or constraint missing that the subject is actually following in performing the lift, i.e., the lift must be faster at the beginning of the lift in order to complete it. By this kind of comparison it is possible to study the problem with a much greater understanding.

CONCLUDING REMARKS

By modeling at the gross musculoskeletal level, the current simulation of manual lifting offers a simple framework that allows future expansion and refinement by incorporating more realistic constraints. At this stage of modeling it is an advantage not to deal with the intricate neural control behavior of the neuro-muscular system. For use as an aid in the ergonomics of manual material handling, this model has the potential to be developed into a diagnostic and predictive tool. Future work includes developing stability constraints, investigating different performance criteria (objective functions), and analyzing the sensitivity of the constraints.

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