BIOMECHANICS OF MANUAL MATERIAL HANDLING THROUGH SIMULATION

C.J. Lin, T.M. Bernard, M.M. Ayoub and J.A. Macedo

Department of Industrial Engineering
Texas Tech University
Lubbock, TX 79409

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 Seireg, 1972). More recently, whole body and three-dimensional modeling allowing more degrees of freedom became successful. Yamaguchi (1990) used a three-dimensional stick man model, consisting of a trunk and legs with 8 degrees of freedom and 10 muscles, to simulate human gait motion. Hatze (1981) used a 17-segment model with 46 major muscle groups to simulate the dynamics of the long jump. This model has 42 degrees of freedom. Badler et al. (1993) developed a model capable of generating various human motions. These computerized human motion models either simulate a specific motion or task, or are too general and versatile, and thus inaccurate for use in specific conditions.

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. These models assume that the body is a set of linked segments with constant inertial properties. When one end of the set of linked segments is subject to loading, kinetic information can be estimated based on rigid body dynamics. 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. The process of data collection and reduction is usually tedious and time-consuming. At best, the biomechanical analysis provides only diagnostics of the task, that is, it only shows the body stresses which occurred under the specific task condition. When task conditions change, new data collection and analysis need to be performed again. The diagnostic analysis, using conventional biomechanical models, is limited in its predictive power since it does not answer what-if questions regarding the changes of subject or task conditions.

With these considerations, 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 human body is modeled as an inverted pendulum consisting of 5 rigid links: lower leg, upper leg, trunk, upper arm, and forearm. The hand is considered part of the forearm and the ankle is assumed to be motionless. 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. For convenience, the rotational angle made with the horizontal by the lower leg is referred to as the angle of the ankle joint. Similarly, the rotational angles made by the upper leg, trunk, upper arm, and lower arm are referred to as the angle of the knee, hip, shoulder, and elbow, respectively. 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 Largragian method. Interested readers are referred to Chaffin and Andersson (1991) for the equations of motion of coplanar occupational biodynamical lifting models. Using optimization concepts, lifting is assumed to be performed in such a way that it minimizes the objective function:

$$\text{minimize} \quad \int_{t=0}^{T}\sum_{i=1}^{5}\left(\frac{M_i(t)}{S_i(t)}\right)^2 dt$$

where S_i is the moment strength of each joint,
         M_i 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 the forms:

$$\theta_l \leq \theta(t) \leq \theta_u,$$
$$\dot{\theta}_l \leq \dot{\theta}(t) \leq \dot{\theta}_u,$$
$$\ddot{\theta}_l \leq \ddot{\theta}(t) \leq \ddot{\theta}_u,$$
$$\dddot{\theta}_l \leq \dddot{\theta}(t) \leq \dddot{\theta}_u$$

where $\theta(t), \dot{\theta}(t), \ddot{\theta}(t), \dddot{\theta}(t)$ are the angular position, velocity, acceleration and jerk of each joint at time t,

$\theta_l, \dot{\theta}_l, \ddot{\theta}_l, \dddot{\theta}_l$ are the lower bounds of $\theta(t), \dot{\theta}(t), \ddot{\theta}(t), \dddot{\theta}(t)$, respectively, for each joint,

and $\theta_u(\dot{\theta}_u, \ddot{\theta}_u, \dddot{\theta}_u)$ are the upper bounds of $\theta(t), \dot{\theta}(t), \ddot{\theta}(t), \dddot{\theta}(t)$, respectively, for each joint.

The bounds on the angular kinematics of each joint are used to restrict the motion according to the normal range of motion kinematics. In addition, the bounds on the jerk are used to ensure a smooth motion pattern.

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 musculo-skeletal 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 Layout 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. They have the forms:

$$if\ \{y_{box}(t) \in (y_{box}(T), y_{box}(T) - h)\}\ then\{[x_{box}(t) + \frac{w}{2} + \delta] - [x_{box}(T) - \frac{w}{2}] < 0\}$$

$$and\ if\ \{y_{knee}(t) \in (y_{box}(t) - \frac{h}{2}, y_{box}(t) + \frac{h}{2})\}\ then\{x_{box}(t) - \frac{w}{2} - (x_{knee}(t) + \delta) > 0\}$$

where $(x_{box}(t), y_{box}(t))$ is the position of the center of box at time t,

$(x_{knee}(t), y_{knee}(t))$ is the position of the knee joint at time t,
h is the height of box in the sagittal plane,
w is the width of box in the sagittal plane,
T is the total lifting time,
and δ is the collision tolerance.

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 $(x_{box}(T), y_{box}(T))$. The horizontal position of the front edge of the table can be estimated by $(x_{box}(T) - \frac{w}{2})$.

The vertical height of the table is $(y_{box}(T) - \frac{h}{2})$. 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

$(y_{box}(T), y_{box}(T) - h)$, the front edge of the box, $(x_{box}(t) + \frac{w}{2})$, cannot move beyond the edge of the table, $(x_{box}(T) - \frac{w}{2})$, in order to avoid collision. Note that the collision tolerance, δ, is used to describe the clearance between the box and table that is needed for the subject to move the box around the edge of the table. Similarly, the second constraint indicates that when the height of knee joint is within the upper and lower edges of the box, the horizontal position of the rear edge of the box should be greater than the horizontal position of the knee plus a tolerance to avoid collision.
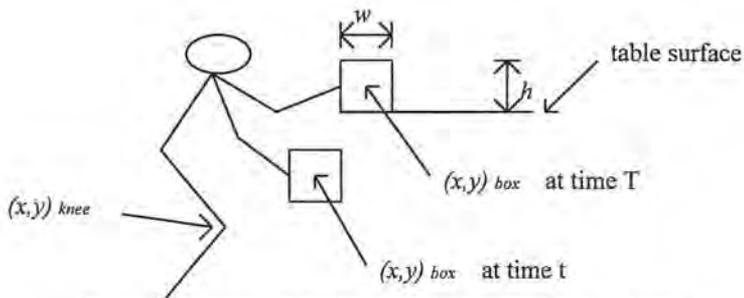

Figure 1. Geometric relationships between the subject, box, and table

Other constraints

There are other constraints that describe the coordination of the movement. They may be used to direct the order in which the joints move, the way the center of gravity moves, or the way the box moves. Some of these constraints are developed based on observations from the actual behavior of the motion. There is little theoretical foundation to provide support for these constraints. Current experimentation is designed to investigate the effects of these constraints on the predicted motion. One example is the constraint on the center of gravity (C.G.) of the system (the subject and the load):

$$\max\{x_{cg}(0) - x_{cg}(0)\} > 0$$
$$\max\{y_{cg}(t) - y_{cg}(T)\} > 0$$

where $x_{cg}(t)$ is the horizontal position of system C.G. at time t,

and $y_{cg}(t)$ is the vertical position of system C.G. at time t.

Note that $x_{cg}(0)$ is the initial horizontal position of system C.G. The first constraint ensures that at least once during the lift, the system C.G. must move backward (closer to body) across the initial horizontal C.G., then move forward so that the box is moved toward its final destination. This constraint imitates the backward motion of the body during lifting. In the second constraint, $y_{cg}(T)$ is the final vertical position of the system C.G. This constraint ensures that at least once during the lift, the system C.G. moves upward across the final vertical position of C.G. before it is lowered down to the final position. This constraint imitates the upward motion of the body during lifting.

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 refered 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 below.

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 2 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.
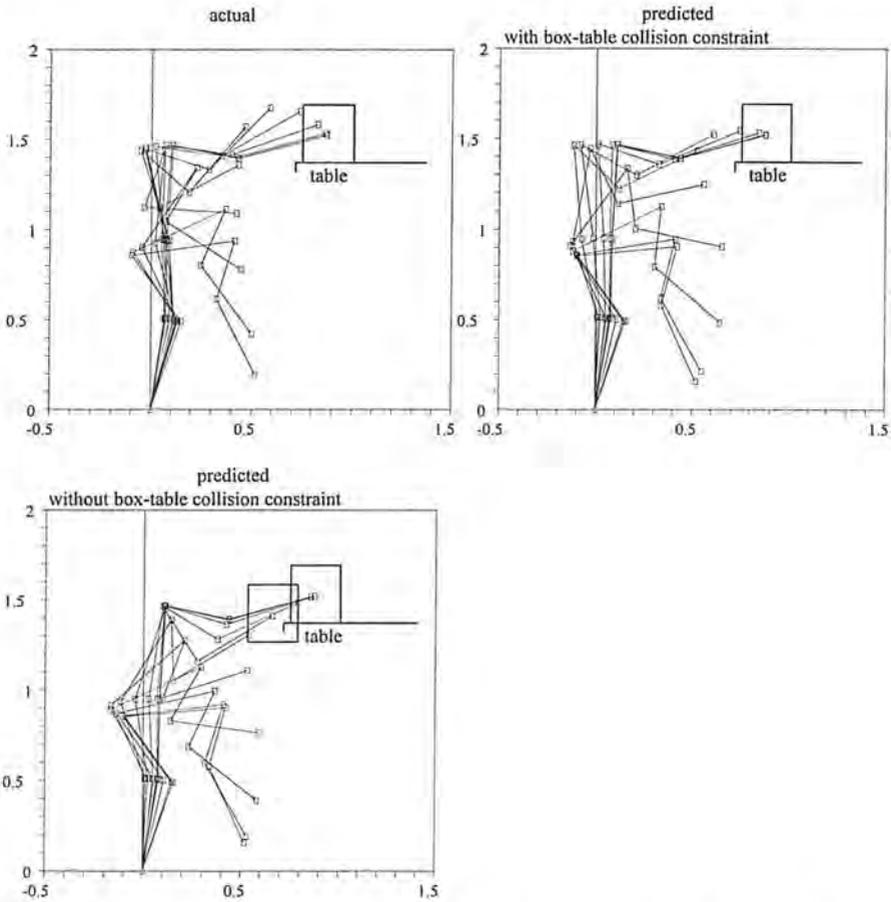

Figure 2. Stick Diagrams of the actual and the predicted (with and without box-table collision constraint) lifts.

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 musculo-skeletal 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.

REFERENCES

Ayoub, M.M. and Hsiang, M.S., 1992, Biomechanical Simulation of a Lifting Task. In: Advances in Industrial Ergonomics and Safety IV, Taylor & Francis.

Badler, N.I., Phillips, C.B., and Webber, B.L., 1993, Simulating Humans, Computer Graphics Animation and Control, Oxford University Press.

Chaffin, D.B. and Andersson, G.B.J., 1991, Occupational Biomechanics, John Wiley & Sons.

Hatze, H., 1981, A Comprehensive Model for Human Motion Simulation and its Application to the Take-Off Phase of the Long Jump. Journal of Biomechanics, 14,135-142.

Hsiang, M.S., 1992, Simulation of Manual Materials Handling, Ph.D. Thesis, Texas Tech University.

Lasdon, L.S. and Waren, A.D., 1979, Generalized Reduced Gradient Software for Linearly and Nonlinearly Constrained Problems. In Design and Implementation of Optimization Software, H. Greenberg, Ed., Sijthoff and Noordhoff Pubs.

Lee, Y.H.T., 1988, An Optimization Model to Evaluate Methods of Manual Lifting, Ph.D. Thesis, Texas Tech University.

Townsend, M.A. and Seireg, A., 1972, The Synthesis of Bipedal Locomotion. Journal of Biomechanics, 5,71-83.

Winter, D.A., 1990, Biomechanics and Motor Control of Human Movement, 2nd Edition, John Wiley & Sons.

Yamaguchi, G.T., 1990, Performing Whole-Body Simulations of Gait with 3-D, Dynamic Musculoskeletal Models. In: Multiple Muscle Systems, Biomechanics and Movement Organization edited by J.M.Winters and S.L.Y.Woo, Springer-Verlag.