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Simulation of manual materials handling: Biomechanial assessment under different lifting conditions

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Abstract. Manual material handling (MMH) tasks were evaluated and compared under different lifting conditions. For the theoretical evaluations, a two-dimensional sagittally symmetric human-body model was established to compute the moment and joint load time histories for MMH tasks for a variety of different lift specifications and constraints such as lifting durations, loads, and modes. Nonlinear control techniques and genetic algorithms were utilized in the optimizations to explore optimal lifting patterns. Since the kinetic measures such as joint moments are vital metrics in the assessment of the likelihood of injury, the simulation results obtained may be compared using these metrics for each lift type, so that the superiority of a lifting method or protocol relative to another may be determined.

Keywords: Lifting, manual materials handling, back pain, squat, stoop, joint strength

1. Introduction

For the last several decades, manual materials handling has attracted great interest from researchers in many disciplines, primarily because of the huge amount of work and financial losses, and human sufferings caused by low back pain and injuries. Consequently, it is a major concern to researchers and organizations to develop means to predict, control, and prevent such injuries. Thus, much research has focused on the establishment of ergonomic workspace designs and employee training.

Biomechanics modeling plays an important role in estimating individuals' lifting capacities, comparing different lifting modes, and designing workspace conditions. Using such models, the potential for injuries

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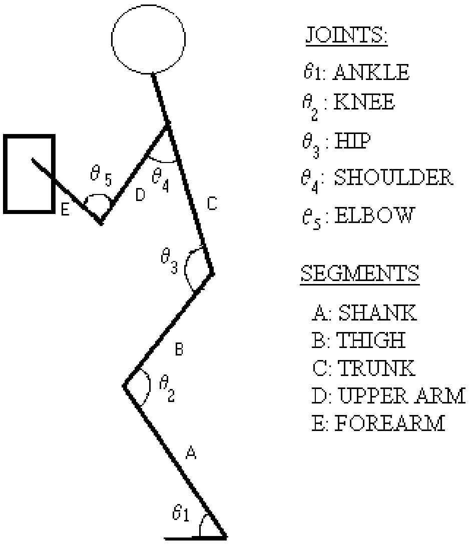

Fig. 1. A two-dimensional sagittally symmetric model for human lifting.

can be estimated in advance and greatly reduce the need for often difficult, expensive and potentially invasive laboratory measurements [7,18,19].

Optimal control techniques are being used to form lifting trajectories and predict associated joint moments during lifting. Optimal control is used in the biodynamics modeling is primarily due to two reasons. First, locomotion is believed to obey a certain "principle of optimality" [2,15]. Since optimal control theory aims to determine the control laws that will minimize (or maximize) an objective function subject to some constraints [12], such techniques, when applied to an adequate dynamic model for the system, provide a practical means for determining muscle forces and joint torques. Secondly, the dynamic model of acceptable accuracy that must be developed for use with the above described optimal control scheme is itself a valuable analysis and assessment tool for the prediction of the muscle forces and joint moments that produce the desired movement. Unfortunately, this dynamic model construction and analysis is not a simple task, given that the musculoskeletal system considered is highly redundant, i.e., the number of independent muscles acting on a particular joint exceeds the number of degrees of freedom of that joint. Moreover, many muscles can affect more than one joint at a time, which brings complex coupling to the system. Therefore, there is no direct or unique solution to the problem of performing a specific task. However, the above-mentioned difficulties can be overcome by using optimal control techniques to estimate muscle forces produced during lifting [2,15,18].

In this paper, moment time histories obtained for different lifting conditions are compared to deduce information on safe lifting patterns. The results obtained to date clearly indicate that one should include kinetic measures in the objective functions to be optimized and in the assessment of lift simulation accuracy and safety [1,6]. The primary reason behind computing moments is that resultant forces at joints can be determined from this information. Since the forces produce stresses in bones, muscles and connecting tissues, and thus contribute directly to injuries. Therefore, while comparing lift performances, the kinetic measures should be considered, because looking at results at kinematics level (e.g. matching

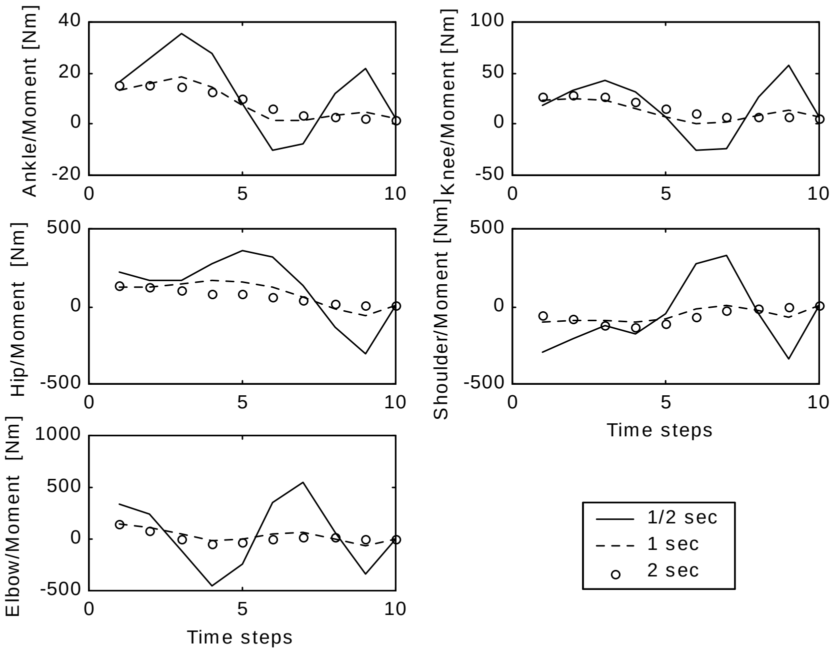

Fig. 2. Comparison of moment-time histories for all joints under different lift durations.

predicted trajectories to those which are experimentally obtained) will not consider these important quantities. With this in mind, kinetic measures, such as moment time histories were compared in this paper to evaluate manners to perform more safe lifts for different lifting conditions such as lift load, mode, and duration.

2. Theory

2.1. Physical model

A two-dimensional sagittally symmetric human body model, Fig. 1, was constructed as a five rigid link mechanism for the biomechanical simulation of manual lifting tasks. These links possessed the same length, mass, and inertia properties as estimated for their human counterparts. Therefore, any movement or configuration could be described with the five generalized coordinates describing the relative orientation of each of these five links with respect to the parent body.

Joints at the ankle, knee, hip, shoulder, and elbow were all treated as one-degree of freedom revolute joints. Spinal column was considered as one rigid link that includes mass of the head and neck appropriately located. The hands were also modeled as parts of the forearms, and their relative motion with respect to forearms were neglected. It was further assumed that subject did not walk with the load during the lift, i.e., foot was fixed on the ground [4,11].

The joint reaction forces and joint moments for a typical rigid link i in an n-link open chain mechanism can simply be obtained by utilizing a Newton-Euler formulation recursively [20].

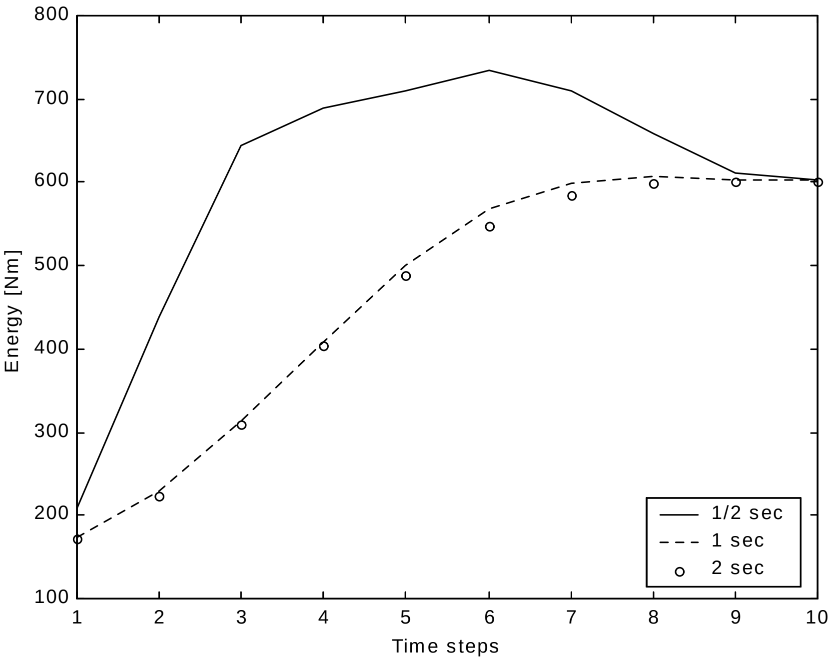

Fig. 3. Energy change of the total lift for different lifting durations.

2.2. Optimization

One of the most significant problems in optimization of biomechanical systems is the choice of a proper cost function reflecting the most important aspects of locomotion and loading. In this paper, it was chosen to minimize "*integration over the time of sum of the square of the ratio of the predicted joint moments to the corresponding joint dynamic strength*" [5,6].

$$J = \int_0^{t_f} \sum_{i=1}^{5} \left[\frac{M_i(\theta,\dot{\theta},\ddot{\theta})}{S_i(\theta,\dot{\theta})} \right]^2 dt \tag{1}$$

where t_f is the lifting duration, M_i are moments and S_i are joint dynamic strengths for the ith joint. In Eq. (1), the moments and the strengths are given in terms of $\theta, \dot{\theta}$, and $\ddot{\theta}$, which represent joint angular displacements, angular velocities and angular accelerations for each joint, respectively. The joint strengths were considered as the measures of joint capacities under different postures and joint angular velocities [9,10].

The dynamic strength values were used in the objective function as opposed to static ones because dynamic strengths better replicate the joint behavior and improve the simulation [9,10]. They were defined to be functions of joint angular positions and velocities for each joint i [8] in the following form

$$S_i(\theta,\dot{\theta}) = \beta_{i0} + \beta_{i1}\theta_i + \beta_{i2}\dot{\theta}_i + \beta_{i3}\theta_i^2 + \beta_{i4}\dot{\theta}_i^2 + \beta_{i5}\theta_i\dot{\theta}_i \tag{2}$$

The coefficients β_1 through β_5 were determined based on experimental results and they were directly taken from [8]. The ratio between the moment and joint strength in the objective function above (Eq. (1)) is called the muscular utilization ratio (MUR).

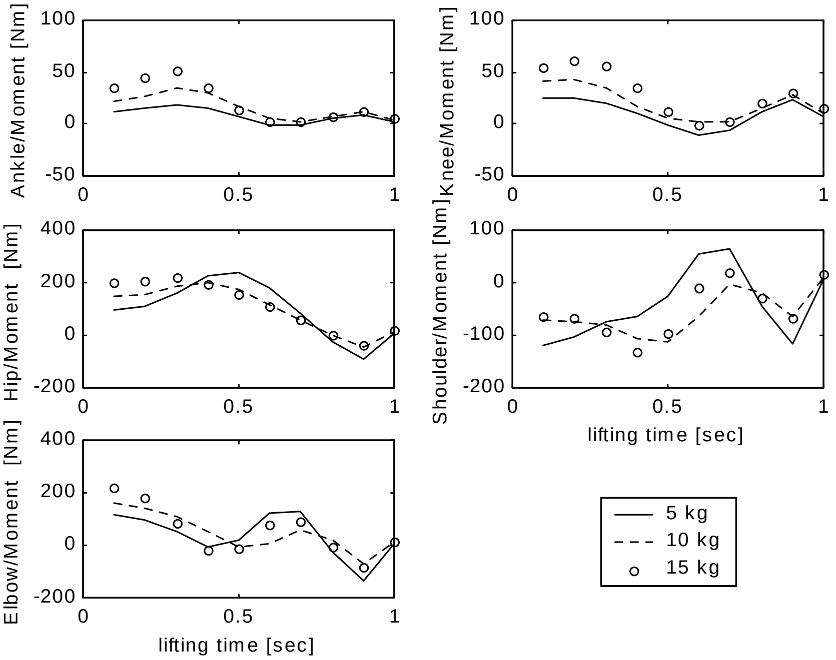

Fig. 4. Comparison of moment-time histories of all joints under different loads.

The constraints on the objective function were of four types: kinematic, kinetic, stability, and penetration. Kinematic constraints were the ones that each joint operate within a certain range. For example, an elbow cannot be extended over 180°. Consequently, every joint shared this type of geometric constraint. The second type of constraint was related to some kinetic measures, in which the maximum moments generated by joints during a lift were restricted not to exceed a certain limit (i.e., a strength capacity). Thirdly, the stability of the body had to be maintained. For this purpose, the center of mass of the subject's body and the load were forced to remain directly over the subject's foot. Lastly, load lifted was forced not to penetrate into the body during the simulations. All these constraints were implemented in the genetic algorithm as penalty functions of cubic order of the error (e.g. constraint violation).

2.3. *Numerical formulation of the problem*

The problem is difficult because it is highly nonlinear and is of infinite dimension. One possible approach is to try problem as a two-point boundary value problem that is parameterized by approximating the states and/or control variables by a polynomial and/or a Fourier series [4,17]. For this study, joint angles were approximated as seventh order polynomial in the form

$$\theta_i = \sum_{j=0}^{7} a_{i,j} t^j \tag{3}$$

for the ith joint. Since the boundary conditions (initial and final angular positions, angular velocities, and angular accelerations) were known for a lifting experiment, six of the coefficients can be determined. The other two coefficients were added to the polynomials to introduce extra degree of freedom for

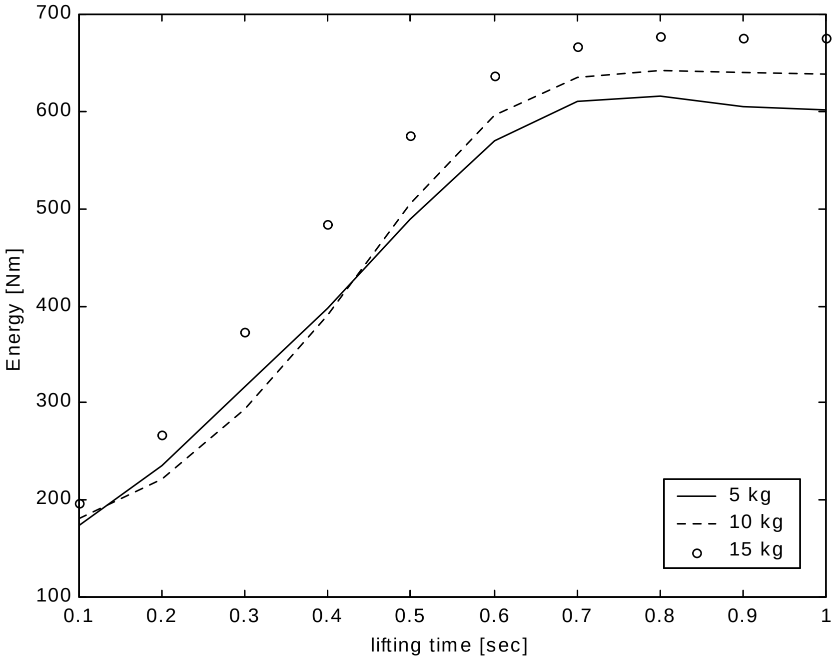

Fig. 5. Energy change of the lift for different loads.

optimization. By substituting these polynomials and their derivatives into Eq. (1), the problem becomes a finite dimensional parameter optimization of the form

$$J = \int_0^{t_f} f_1(a_{i,j}, t)dt \tag{4}$$

where i is the joint number, and j coefficient index of the polynomial. Since the lifting duration is known, the problem can further be simplified by discretization in integration time steps of Δt as

$$\Delta t = \frac{t}{k} \tag{5}$$

where t is time, k is the number of integration steps. Then, the problem becomes minimizing another function including only the polynomial coefficients, $a_{i,j}$, and the integration step size, Δt as follows

$$J = f_2(a_{i,j})\Delta t \tag{6}$$

Once the coefficients in the polynomial are estimated, the optimized path and moments for a lifting task can easily be determined.

A genetic algorithm implementing Goldberg's [3] algorithm in MATLAB® was developed for optimizations. It used fixed population size with string length of 30, a crossover probability, P_c, of 0.001, and a mutation probability rate, P_m, of 0.002.

3. Results and discussion

The simulation and prediction program was coded for designing sagittally symmetric lifting tasks and for utilization as a computer experimentation tool that provides an extensive amount of information

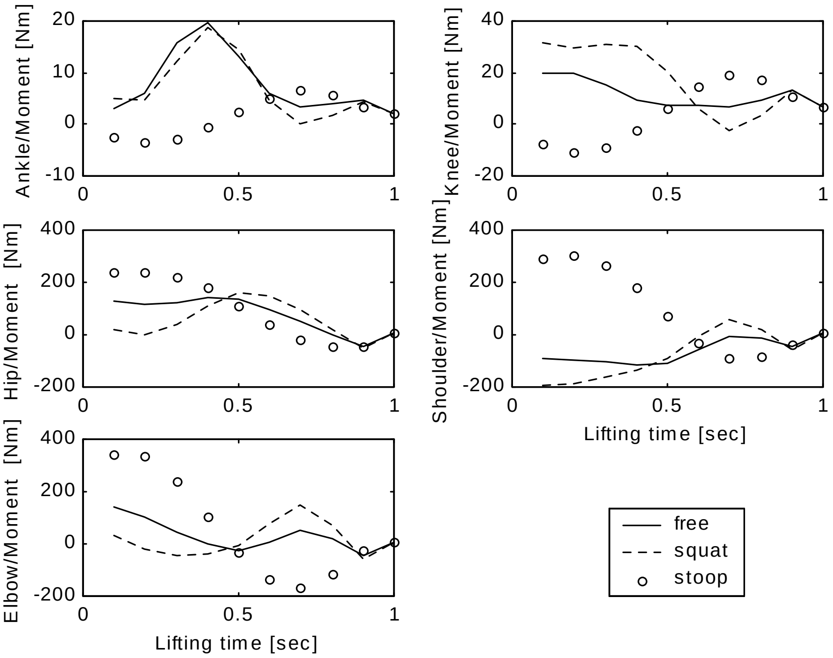

Fig. 6. Moment time history for each joint for different modes of lifting.

about movements, and inter-joint loads under different lifting scenarios. For example, if the specified lifting duration is changed, the predicted effect of this change on joint moment levels may be easily investigated. In this manner, the analyst may similarly investigate the individual effects of various system parameters on lifting (task execution) performance, and assess the likelihood of incurring injury. Examples include, but are not limited to, consideration of individual's specific body structure (height, weight, body geometry, etc), individual's specific constraints (e.g. presence of prior injury, or disability, etc.), or modification of task objective or task execution protocol.

3.1. Effect of lifting duration

As an example, given below are the results for three different lifting durations, specifically 0.5 sec (fast), 1 sec (moderate), and 2 sec (slow), for a subject with mass of 94.7 kg, height of 1.85 m. For this purpose, all other parameters are held constant. The load lifted was 5 kg. Sample results for joint moment changes were given in Fig. 2 for subject's all joints, and the total energy change for the lift in Fig. 3.

These results are presented with respect to the ten equally spaced time steps during the three lifting durations in the simulation and measured data, i.e. the 1st and 10th steps represent the beginning and the end of the lift.

It is obvious from Figs 2 and 3 that higher levels of joint moments, as well as significantly more energy are required in fast lifting. Although the change in energy of the payload from a pure physics (conservative system) perspective is the same for each case, energy expended in lifting or accelerating a body cannot be reclaimed because the human form is not a conservative system. Thus, if one too greatly increases the rate at which a task is accomplished, the task may require over exertion, which can be injurious to the individual involved. It is also interesting to observe that the plots collapse upon one another as the task duration increases so that the system becomes effectively quasi-static.

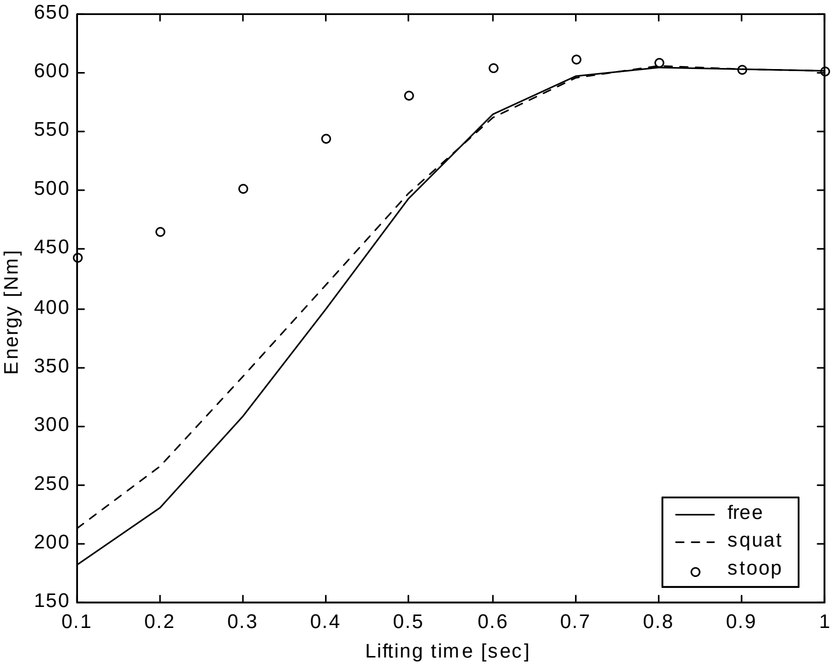

Fig. 7. Total energy change of the lift for different modes of lift.

3.2. *Effect of load mass*

Keeping the time and other parameters unchanged in this example, the mass of the load to be lifted is increased from 5 kg to 10 kg and 15 kg for a subject with a mass of 94.7 kg and a height of 1.85 m, with the associated results provided in Figs 4–5.

The results predicted are consistent with what one would physically expect. Specifically, an increase in load lifted requires more energy consumption (Fig. 5). Also, higher levels of moment applications are necessary to accomplish the task, especially at the start of the lift (see Fig. 4). Therefore, it can be advised here that one should not lift a load that is sufficiently heavy to require a joint moment that exceeds the associated joint strength for the individual, which can be injurious.

3.3. *Effect of lifting mode*

In this case, all parameters were kept constant, except the initial angular positions of body segments. They were changed so as to have a lifting mode of a squat, a stoop, or a free lift. In the stoop, the ankles and knees were kept straight, whereas in the squat, the back was kept to be vertical during the lift. The results for the three aforementioned cases for a subject with a mass of 94.7 kg and a height of 1.85 m were given in Figs 6–7.

As seen from moment diagrams (Fig. 6), stooping requires more exertions in the hip, shoulder and elbow joints, whereas squatting requires higher moments at ankles and knees, as expected. However, free lifting requires the most moderate moment exertion levels in almost all joints. As also obvious from the total energy of the lift (see Fig. 7), the most demanding job is the stooping. The lowest energy requirement is in the free lifting. Therefore, it is advised that one should choose a free style when lifting. This was also concluded by other researchers in the literature based on other criteria [13,14].

4. Discussion

A prediction program was developed to simulate the manual materials handling tasks for investigating the effects of different parameters such as lifting duration, load, and mode. The program was coded in MATLAB [16], which provides users a very rich collection of functions in mathematics, plotting and animation of the results.

The prediction program first approximates the states of the system in the equation of motion, which are derived via a Newton-Euler formulation. Then, this program optimizes the system performance with respect to the objective function, which is postulated as "*integration over the time of sum of the square of the ratio of the predicted joint moments to the corresponding joint dynamic strength*" [6]. Genetic algorithms are then used in the optimization portion of the program which returns estimates for the coefficient values for the seventh order polynomials in time, which are associated with each predicted joint angle time history. Lastly, this optimized coefficient information is fed back to the equations of motion to simulate the lifting motion, and to obtain joint loads and moments.

In making a quantitative comparison of the safety of different lift conditions, it is imperative that predictions be made on kinetic measures such as moment time histories [1,6]. As stated previously, these moments are keys to assessing likelihood of injury. Moreover, these quantities directly affect the system accelerations and angular accelerations, which in turn will influence displacements, rates and thus joint strengths. With this in mind, it is proposed that the objective functions used in evaluating the safety of lifts should involve appropriate kinetics measures. In this paper, moment time histories for different lift durations (slow, moderate, and fast), lift modes (squat, free, and stoop), and lift loads (light, medium, and heavy) were computed and compared.

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