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IMPORTANCE OF KINETIC MEASURES IN TRAJECTORY PREDICTION WITH OPTIMAL CONTROL

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ABSTRACT

A two-dimensional sagittally symmetric human-body model was established to simulate an optimal trajectory for manual material handling tasks. Nonlinear control techniques and genetic algorithms were utilized in the optimizations to explore optimal lifting patterns. The simulation results were then compared with the experimental data. Since the kinetic measures such as joint reactions and moments are vital parameters in injury determination, the importance of comparing kinetic measures rather than kinematical ones was emphasized.

Key Words : Lifting, Optimal trajectory, Back pain, Joint dynamic strengths

OPTİMAL KONTROL İLE YÖRÜNGE TAHMİNLERİNDE KİNETİK ÖLÇÜTLERİN ÖNEMİ

ÖZET

Elle materyallerin taşınımı/kaldırımı için gerekli optimal yörüngelerin similasyonu amacıyla, insan vücudu iki boyutta ve sajital düzleme göre simetrik olarak modellendi. Nonlineer kontrol teknikleri ve genetik algoritmalar, optimal kaldırma yollarını araştırmak üzere optimizasyonlarda kullanıldı. Daha sonra similasyon sonuçları, deneysel verilerle karşılaştırıldı. Kinematik ölçütlerden ziyade, yaralanmaların önceden tahmininde çok önemli olan mafsal kuvvetleri ve mafsallardaki momentler gibi kinetik öçütlerin karşılaştırılmasının gereği vurgulandı.

Anahtar Kelimeler : Kaldırma, Optimal yörünge, Bel ağrısı, Mafsal dinamik mukavemeti

1. INTRODUCTION

Although it has always been desirable to determine muscle forces and joint moments for predicting possible low back injuries during manual material handling (MMH) tasks, there is unfortunately no device to directly measure muscle forces non-invasively (Pandy et all., 1995). Consequently, biomechanical modeling becomes a necessary tool for muscle stress analysis on the musculoskeletal system, particularly on the lumbar spine. These models also serve as an estimation tool for kinematics and kinetics of the motion (Hsiang and Ayoub, 1994). A number of researchers have recently applied optimal control theory to the analysis of human locomotion with the idea that it is a practical tool for explaining the control of the human musculoskeletal system, and as such it may successfully be used in predicting biodynamic behavior (Hsiang and Ayoub, 1994; Pandy et all., 1992).

Optimal control techniques are being used in the biodynamics modeling primarily due to two reasons. First, since the locomotion is believed to be obeying a certain "principle of optimality" (Chow and Jacobson, 1971; Ma, 1994), and the optimal control theory aims to determine the control laws that will minimize (or maximize) an objective function subject to some constraints (Kirk, 1970), such techniques provide a means for determining muscle forces and joint torques. Secondly, a dynamic model should be developed to predict the muscle forces and joint moments that produce the movement. However, 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. So, there is no direct solution to the problem. Consequently, the above-mentioned difficulties can be overcome by using optimal control techniques to estimate muscle forces produced during lifting (Chow and Jacobson, 1971; Ma, 1994; Pandy et all., 1992).

2. EXPERIMENTS

Ten healthy male and ten healthy female subjects participated in experiments after signing a consent form approved by the human subjects committee. Concisely, each subject lifted and lowered a two-handles attached to the arm of the LIDOLift in the Biodynamics Laboratory of The Ohio State University. The lifting took place in the sagittal plane of the subject, i.e., both hands and legs were in unison. Each subject was instructed to lift and lower the box from as low as he/she could comfortably reach to waist height, for five continuous repetitions. Before the actual testing, the subject practiced at different loads, techniques, and movement times to gain familiarity with the equipment and testing protocol. Then, the tests were repeated for three (two for females) simulated loads, three techniques of lift, and three movement times of lift in a random order. The simulated masses for the study were 6.8, 13.6 and 20.5 kilograms. Female subjects did not perform the 20.5 kg lifts. The techniques were a free style, stoop (straight-knee), and squat (bent-knee) techniques of lifting. The movement times were 2, 4 and 6 seconds per cycle. The subject was paced to complete the lifts in these times by a metronome. Further analysis verified that the movement times were approximately 2, 4 and 6 seconds per lift. The 27 (18 for females) conditions within lift device were randomized for each subject.

The joint angular position data from the middle three cycles of each lifting condition were fit to 128 point curves and then averaged. This was performed so that a trial of any length time could be compared with any other trial. The angular position data were filtered with a 4th order Butterworth low-pass filter with a cutoff frequency of 4.0 Hz (determined from residual analysis (Winter, 1990)) and then, numerically differentiated using the Taylor Series expansion to compute the angular velocities and accelerations (Chapra and Canale, 1998). The same process of filtering at the same cutoff frequency was repeated to smooth out the noise introduced by numerical differentiation to the computed angular velocities and accelerations.

3. THEORY

3. 1. Physical Model

A two-dimensional sagittally symmetric human body model was established 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 five generalized coordinates of these five links.

Joints at the ankle, knee, hip, shoulder, and elbow were all assumed as one-degree of freedom revolute joints. Spinal column was considered as one rigid link that includes mass of the head and neck. 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 was not walking with the load during the lift, i.e., foot was fixed on the ground (Khalaf et all., 1996; Gruver and Sachs, 1980).

3. 2. Dynamic Model

For a typical rigid link *i* (Figure 1) in an *n*-link open chain mechanism, the joint reaction forces and joint moments can simply be obtained by utilizing the Newton-Euler formulation recursively as,

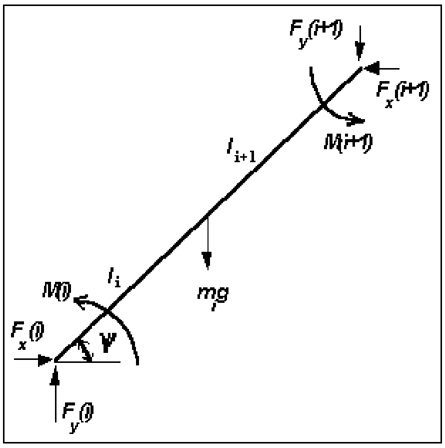

Figure 1. A typical rigid link in an n-link open chain mechanism

$$F_{x,i} = F_{x,i+1} + m_i a_{x,i} \tag{1}$$

$$F_{y,i} = m_i g + F_{y,i+1} + m_i a_{y,i} \tag{2}$$

$$M_i = -M_{i+1} + (F_{y,i+1} l_{i+1} + F_{y,i} l_i)\cos(\psi) - (F_{x,i} l_{i+1} + F_{x,i} l_i)\sin(\psi) + I_{zz}\ddot{\psi} \quad (3)$$

The parameters used in these formulations are explained below:

$F_{x,i}$ and $F_{x,j}$	:	Forces at the joints i and i+1 in x-direction,
$F_{y,i}$ and $F_{y,j}$	:	Forces at the joints i and i+1 in y-direction,
M_i and M_{i+1}	:	Moments in opposite directions acting at joints i and i+1,
m_i	:	Mass of the link,
l_i and l_{i+1}	:	Lengths from center of mass to joints i and i+1,
$a_{x,i}$ and $a_{y,i}$	:	Accelerations in x- and y- directions,
g	:	Gravitational acceleration,
I_{zz}	:	Mass moment of inertia about z axes (perpendicular to both x and y),
$\psi, \dot{\psi}$ and $\ddot{\psi}$	:	Angular displacement, velocity, and acceleration of the link, respectively.

3. 3. Optimization

One of the most significant problems in optimization of biomechanical systems is the choice of a proper cost function reflecting most of the aspects of locomotion. 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" (Gündoğdu, 2000). The joint strengths were considered as the measures of joint capacities under different postures and joint angular velocities.

$$J = \int_0^{t_f} \sum_{i=1}^{5} \left[\frac{M_i(\theta, \dot{\theta}, \ddot{\theta})}{S_i(\theta, \dot{\theta})} \right]^2 dt \quad (4)$$

where t_f is the lifting duration, M_i moments and S_i joint dynamic strengths for the i^{th} joint. The dynamic strength values were used in the objective function as opposed to static ones to better replicate the joint behavior and to improve the simulation. They were defined to be functions of joint angular positions and velocities for each joint i (Khalaf, 1998) in the following form

$$S_i(\theta, \dot{\theta}) = \beta_{i0} + \beta_{i1}\theta_i + \beta_{i2}\dot{\theta}_i + \beta_{i3}\theta_i^2 + \beta_{i4}\dot{\theta}_i^2 + \beta_{i5}\theta_i\dot{\theta}_i \quad (5)$$

The coefficients β_1 through β_5 determined based on experimental results were directly taken from (Khalaf, 1998). The ratio between the moment and joint strength in the objective function above (Eq. 4) is called the muscular utilization ratio (MUR).

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^o. Consequently, every joint had the same type of geometric constraint. The second type of constraint was related to some kinetic measures, in which the maximum moment generated by a joint 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 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.

3. 4. Numerical Formulation of the Problem

The problem is highly nonlinear and an infinite dimensional one. One of the approaches to solve two point boundary value problems at that nature is to approximate the states and/or controls by a polynomial and/or a Fourier series (Gruver and Sachs, 1980; Nagurka and Yen, 1990). For this study, joint angles were approximated as seventh order polynomial in the form,

$$\theta_i = \sum_{j=0}^{7} a_{i,j}\, t^j \quad (6)$$

for the i^{th} 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 optimization. By substituting these polynomials and their derivatives into equation (4), the problem becomes a finite dimensional parameter optimization of the form,

$$J = \int_0^{t_f} f_1(a_{i,j}, t)\, dt \quad (7)$$

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,

$$\Delta t = \frac{t}{k} \quad (8)$$

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,

$$J = f_2(a_{i,j})\Delta t \tag{9}$$

A genetic algorithm implementing Goldberg's (Goldberg, 1989) algorithm in Matlab was used for optimizations. Once the coefficients in the polynomial are estimated, the optimized path for a lifting task can easily be determined. Sample results for a randomly selected subject (mass of 94.7 kg, height of 1.85 m) were given in Fig. 2-4 for his hip joint that is the most critical one in lifting.

4. DISCUSSION AND CONCLUSION

A two dimensional, sagittally symmetric model was established to simulate manual lifting tasks. Joint reaction forces and joint moments for the five rigid-links describing human body in two-dimension were obtained with the use of Newton-Euler formulation. Then, the aforementioned objective function (Eq. 9) was formed based on these moments.

As mentioned before, *dynamic strength* values were used in the objective function with the belief that they are dependent not only on joint angular position but also on joint angular velocities (Khalaf, 1998). Minimizing an objective function composed of pure moments or moments with *joint static strengths* embedded does not guarantee that the maximum levels of exertions (moments) will be bounded by the allowable upper and lower limits of the joints under investigation. Although they minimize the integrated square of moments causing the movement, the moments might be at times exceeding the allowable joint strengths. Since an upper limit is prescribed with joint strengths, an objective function including MUR would be more effective in designing safe lifting tasks. Furthermore, using strength values specifically obtained for the same subjects rather then normalized ones in the literature (Hsiang, 1992) brought additional power to our model.

When the simulation results were compared with the experimental findings, they exhibited a good consistency with the data. Randomly chosen sample results were given in Figure 2-4 for the hip angle that is the most critical one in lifting operations. As opposed to some other researchers, not only was presented here the results at kinematic level but also the ones at kinetic level. Specifically, presenting the kinematical results such as angles, and then deriving conclusions based only on those results may lead to an erroneous or at least inadequate conclusion. However, presenting results at both kinematic and kinetic level, and deriving conclusions based on these two is much safer way to proceed in such a research. Therefore, the kinetic measures such as loads and moments, not positions, should be the ones that indicate the quality of a simulation best (Anderson and Gundogdu, 2000).

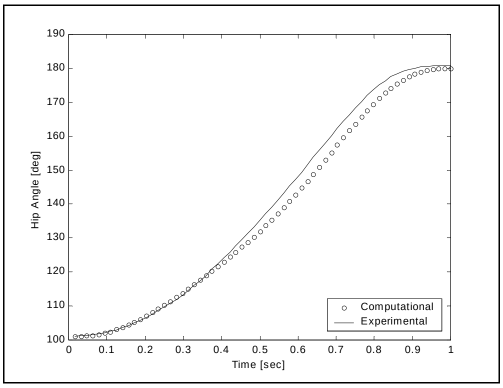

Figure 2. Comparison of an experimental and a theoretical motion trajectory for the hip joint

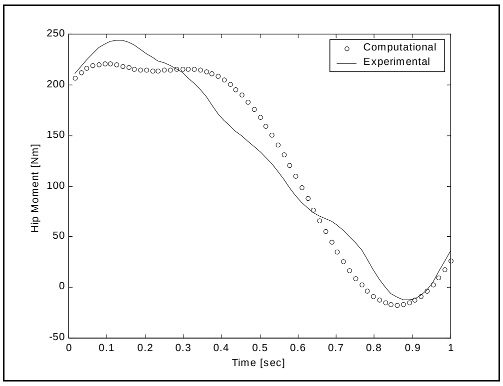

Figure 3. Comparison of an experimental and a theoretical moment change for the hip joint

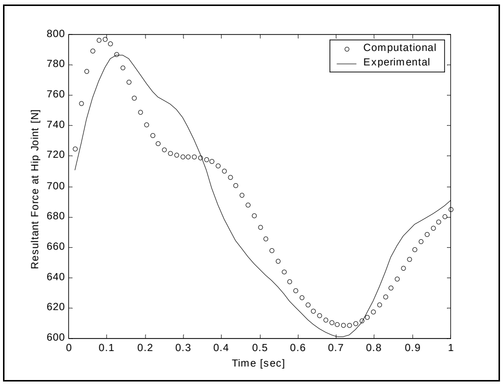

Figure 4. Comparison of an experimental and a theoretical force resultant for the hip joint

It was another strength of this paper to use Genetic Algorithms (GA) to optimize objective function as opposed to other researchers (Gruver and Sachs, 1980; Hsiang, 1992; Hsiang and Ayoub, 1994; Khalaf et all., 1996) who used generalized reduced gradient algorithms. Since GAs search from population of points, not a single point, they have better chance to catch global optimum as compared to other heuristic methods, although they don't guarantee global optimum. Furthermore, they don't require any derivative information, they just use objective function evaluations, which brings another ease to researchers because getting derivative information is cumbersome in many cases, especially for highly nonlinear systems such as biomechanic ones (Goldberg, 1989).

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