DEVELOPMENT OF A GENETIC ALGORITHM BASED BIOMECHANICAL SIMULATION OF SAGITTAL LIFTING TASKS

Ömer Gündoğdu[1], Kurt S. Anderson[2], Mohamad Parnianpour[3]

[1]Atatürk University, Department of Mechanical Engineering, Erzurum, Turkey
[2]Rensselaer Polytechnic Institute, Mechanical, Aerospace, & Nuclear Engineering, Troy, New York
[3]Sharif University of Technology, Department of Mechanical Engineering, Tehran, Iran

ABSTRACT

Fibrin sealant and platelet gels are human blood-derived, biodegradable, non toxic, surgical products obtained by mixing a fibrinogen concentrate or a platelet rich plasma with thrombin, respectively. Fibrin sealant is now a well known surgical tool increasingly used to stop or control bleeding, or to provide air and fluid tightness in many surgical situations. Platelet gels are newly developed preparations that are of specific interest because they contain numerous physiological growth factors and cytikines that are released upon the activation of blood platelets by thrombin. These growth factors, including PDGF, TGF- β1, BMP, and VEGF have been shown to stimulate cell growth and differentiation with special clinical benefits for soft and bony tissue healing and regeneration. Platelet gels allow surgeons to manipulate the cellular environment of surgical sites and to guide tissue regeneration. A specific interest of such products is observed for the induction of osteogenesis and chondrogenesis. Advances in the preparation, clinical use, and safety of these two important classes of blood-derived biomaterials are reviewed.

Biomed Eng Appl Basis Comm, 2005(February); 17: 12-18.
Keywords: Lifting, optimal trajectory, back pain, joint dynamic strengths, moment minimization, injury prediction.

1. INTRODUCTION

Although it has always been desirable to determine muscle forces and joint moments as an aid in evaluating the likelihood and severity of possible low back injuries during manual material handling (MMH) tasks, there is unfortunately no device to directly measure muscle forces non-invasively [21]. Consequently, biomechanical modeling becomes a necessary tool for muscle stress and joint load analysis on the musculoskeletal system, particularly on the lumbar spine. These models also serve as a tool for the estimation of the kinematics and kinetics of the motion [12]. 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 [12,20].

Optimal control techniques are being used in the biodynamics modeling primarily due to two reasons. First, locomotion is believed to obey a certain

Received: May 27, 2004; Accepted: Jan 25, 2005
Correspondence: Mohamad Parnianpour, Professor
Sharif University of Technology, Department of Mechanical Engineering, Tehran, Iran
E-mail: parnianpour@sharif.edu

"principle of optimality" [4,18]. Since optimal control theory aims to determine the control laws that will minimize (or maximize) an objective function subject to some constraints [17], such techniques, when applied to an adequate dynamic model for the system, provide a practical means for determining muscle forces and joint torques. Secondly, a dynamic model of acceptable accuracy should be developed to predict the muscle forces and joint moments that produce the desired movement. Unfortunately, this dynamic model construction and analysis is no 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 [4,18,20].

Simulations of human movements are very important in the fields of preventive health care, computer aided rehabilitation, work-space design, basic motion research, and sports. This is because an accurate simulation can provide information about some quantities-which may not be directly measured, such as joint reactions, as described previously. Additionally, accurate computer simulation based predictions could provide a means to easily, safely, and cheaply explore new task execution options. Such simulation tools could also serve as means for injury prediction without having to conduct the actual movement [10]. Therefore, a prediction tool that has been developed is presented in this paper to estimate and animate manual materials handling tasks. The program estimates the motion, the joint moments, work done on each joint, and animates the lift in a graphical environment for a given set of inputs.

2. EXPERIMENTS

Ten healthy male and ten healthy female subjects participated in experiments after signing a consent form approved by the human subjects committee at The Ohio State University. Concisely, each subject lifted and lowered the 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 subjects each 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 employed 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 the 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 [22]) and then, numerically differentiated using the Taylor Series expansion to compute the angular velocities and accelerations [3]. The same process of filtering at the same cutoff frequency was repeated to smooth out the noise introduced by numerical differentiation, which was used to compute angular velocities and accelerations from the experimentally determined discrete position data.

3. THEORY

3.1 Physical Model

A two-dimensional sagittally symmetric human body model 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 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 motions 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 [7,16].

The joint reaction forces and joint moments for a typical rigid link in an n-link open chain mechanism can simply be obtained by utilizing the Newton-Euler formulation recursively [23].

3.2 Optimization

One of the most significant problems in optimization of biomechanical systems is the choice of a proper cost function which must adequately reflect the most important aspects of the locomotion. In this paper, this objective function was chosen to minimize the "*integration over the time of the sum of the square of the ratio of the predicted joint moments to the corresponding joint dynamic strength*" [8-9].

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

where t_f is the lifting duration, M_i moments and S_i joint dynamic strengths for the i^{th} joint. In the equations, the moments and the strengths are given in terms of θ , $\dot{\theta}$, 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 [14-15].

The dynamic strength values were used in the objective function as opposed to static ones because dynamics strengths better replicate the joint behavior and improve the simulation [14-15]. They were defined to be functions of joint angular positions and velocities for each joint i [13] in the following form

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

The coefficients β_1 through β_5 were determined based on experimental results, and were directly taken from [13]. 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, the elbow cannot be extended over 180° . Consequently, every joint had a similar 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., joint's maximum muscular 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 - its base of support. Lastly, the loads lifted were forced not to penetrate into the body during the simulations. All these constraints were implemented in the genetic algorithm as penalty functions of the cubic power of the error (constraint violation magnitude) generated.

3.3 Numerical Formulation of the Problem

The problem is highly nonlinear and an infinite dimensional one. One of the possible approaches for making the solution of this problem more tractable is the parameterization of the motion between the known (prescribed) end points. This can be accomplished by formulating the problem as a two-point boundary value problem with the intermediate state and/or control variables approximated by a polynomial and/or a Fourier series [7,19]. For this study, joint angles were approximated as seventh order polynomials in the form

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

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 degrees-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

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

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

$$\Delta t = \frac{t}{k} \qquad (5)$$

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

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

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

A genetic algorithm implementing Goldberg's [6] algorithm in MATLAB® was used for the 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.

4. THE SIMULATION PROGRAM

A schematic of the prediction program for manual materials handling tasks is given in the figure below (Fig. 1). As shown in the figure, the program is composed of mainly three parts: i) Approximation and equations of motion; ii) optimization; and iii) simulation and animation. The inputs, the main stages of the program, and the outputs are explained in detail in separate paragraphs in the following pages.

4.1 Inputs

The inputs to the prediction program are listed as the subject’s mass, subject’s anthropometrical measures, age and gender, mass of the load to be lifted, duration of the lift, initial and final conditions of the angular positions of the body segments, and the choice of either static or dynamic strength to be used in optimizations. Except age, gender, and strength type, all of the inputs mentioned above have direct impact on reaction forces in the joints and joint moments causing the movement, because the equations of motions derived are functions of subject's mass, subject’s anthropometrical data, etc. However, age and gender affect joint strengths that are used in the objective functions, and are further used also for deciding whether a task is safe for a person performing the task.

Age: One of the criteria affecting muscle strengths is reported to be age. The highest strength is achieved in the late 20's and early 30's, and gradually declined thereafter [5]. As a person reaches to age 40, his/her strength approximately drops 5% below his/her peak value. By the age 65, it is 20% below the highest strength. However, it should also be noted that the rate of decline in muscle strength could be significantly affected through a training regimen [2]. When the prediction program is provided with the subject’s age, it multiplies the joint strength values with the pre-interpolated percentages based on the above data.

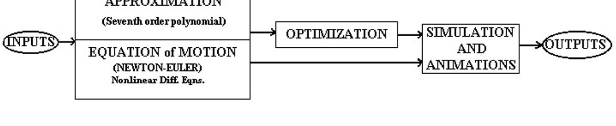

Fig 1. The schematic of the prediction program.

Gender: There is a distinct difference in muscular strengths between men and women. In general, a man's mean strength is approximately 35% higher than a woman's, however the difference varies among muscle groups. For example, certain muscle groups such as lower extremity groups in women tend to perform better relative to those in men, while upper extremity ones perform poorer [2].

4.2 The Simulation Program

The program has three stages. The first stage is the portion where the equations of motion, which describe the system, are formed. As described previously, the Newton-Euler formulation was used to develop the equations of motion. These equations are second order nonlinear ordinary differential equations describing the lifting for a given duration. Human anthropometrical data such as mass, inertia, and center of mass ratios of the human body segments were taken from Chaffin and Andersson [2], and Winter [22]. In the first stage again, angular positions are approximated as seventh degree polynomials. These two information files are then fed into the optimization stage where the objective function formed in terms of unknown polynomial parameters are minimized according to the choice of optimization criterion, namely moment minimization with either joint static or dynamic strengths. In the third stage, simulation and animation part of the program is realized based on the optimization results from second stage. The optimization results (the optimal coefficients) are then fed back to differential equations of motion to simulate and animate the motion. It should be noted that once the coefficients are known the equations of motions is evaluated using inverse dynamics which is based on nonlinear algebraic equations while the original forward dynamics problem would have required integration of a highly nonlinear second order ordinary differential equations. One of the advantages of this approximation technique is to use nonlinear programming instead of optimal control theory applied to two-point boundary value problem. All the results are printed on the screen as graphical outputs.

4.3 Outputs

The outputs of the program are, to a significant degree, in the form of graphs and plots. These outputs can be listed as angular position changes, moment and work time histories, total energy change of the lift, absolute trajectory of the load, and animation of the lift. Angular position changes during the lift are plotted for all joints. Together with the absolute trajectory of the load and the animation, they provide a strategy about how to design a lift. Sample results are given in the next section.

The moment-time history graph generated is a crucial one because this plot shows the joint strengths that serve as the safety limits for each joint in the human body. If the predicted moments are lower than the computed joint strengths, then the lift is said to be safe. It is advisable to design tasks requiring joint moments lower than worker' s joint strength, because exertions higher than one' s strength values have higher risk of injuries and those utilization ratios closer to one will results higher rate of fatigue which could reduce the control and coordination of the subject [2].

4.4 Sample Results

As mentioned before, the prediction code was programmed in the MATLAB environment. When the program is called from within MATLAB prompt, it asks from user to provide answers to the following questions:

- Enter the mass of the person [kg]
- Enter the height of the person [m]
- Enter the mass of the load to be lifted [kg]
- Enter the age of the person [years]
- Enter the gender of the person [male or female]
- Enter the duration of the lift [sec]
- Enter the initial angular positions of the body segments [deg]
- Enter the final angular positions of the body segments [deg]
- Enter the choice of the strength type [static or dynamic]

As a sample run, a 25 year old male subject having a mass of 65 kg, a height of 1.65 m was supposed to lift a load of 5 kg from [50 5 15 40 145] degrees initial segment position to [90 180 180 10 180] degrees final segment position in 1.5 sec lift duration. The angles given in brackets are the initial and final relative angles for the ankle, knee, hip, shoulder, and elbow joints, respectively. Sample results are given in the following figures (Fig. 2-4) for joint dynamic strengths.

It can be deduced from Fig. 2 that the lift is a safe one for the hip joint because the moment-time history predicted for the given conditions is below the joint dynamic strength computed for the same person at the same conditions. It can further be concluded from Fig. 3 that one must bring the load closer to himself/herself just after the load being lifted from the floor. This is in an agreement with what the moment minimization aims. The closer the load is brought to the body, the smaller the joint moments will be. Hence, it is advisable for a person to realize this fact while lifting.

In the following figure (Fig. 4), the individual

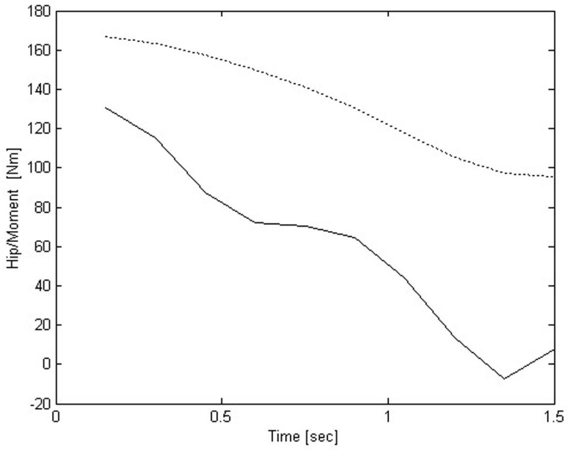

Fig 2. Predicted hip joint-moment (solid line) compared with its dynamic strength (dotted line)

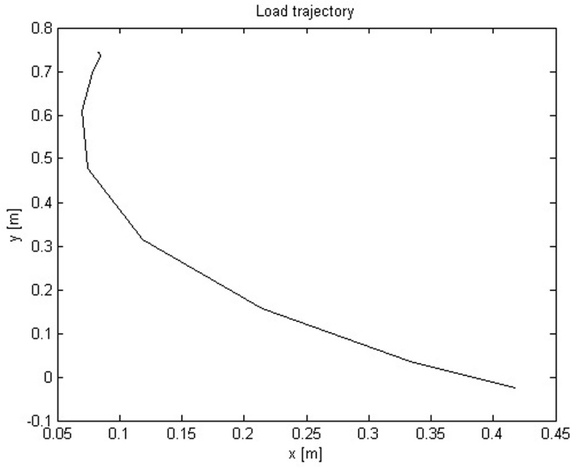

Fig 3. Absolute trajectory of the load.

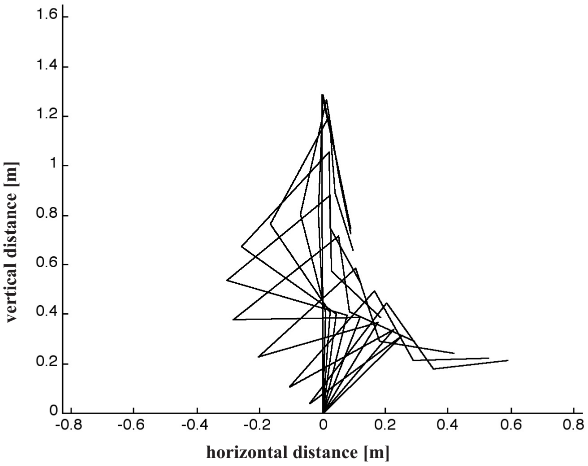

Fig 4. Animation of the lift.

frames of an animation of the lift for the given conditions are presented in a stroboscopic manner on a single frame. One can observe that the optimal path for the joint angle changes as well as the absolute path of the load while the program runs.

5. DISCUSSION AND CONCLUSION

A two dimensional, sagittally symmetric model was constructed 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. 6) 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 [13-15]. However, in the prediction program, the user was also given an option to choose joint static strengths. 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.

When the simulation results were compared with the experimental findings, they exhibited a good consistency with the experimental data. Randomly chosen sample results were given in Fig. 2-4 for the hip angle that is the most critical one in lifting operations. Unlike many other researchers, the results presented here include kinetic quantities such as joint loads and moments, as opposed to purely kinematic quantities such as the payload trajectory. 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. This is because it can be shown that many proposed objective functions produced trajectories which appear to match the experimental results well, but fail terribly in matching the kinetic quantities such as moments and joint loads [1, 8-9]. This is particularly important when one realizes that injury is to a significant degree dependent on muscle stress and joint loads, which are kinematic quantities. Therefore, the kinetic measures such as loads and moments, and not just positions, should be the metrics that indicate the quality of a simulation [1].

Another strength of the approach taken in this paper is the use Genetic Algorithms (GA) to optimize objective function as opposed to other researchers [7,11-12,16] 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. If the system is multi-modal, then other heuristic methods tend to find the closest local optima although GAs don't guarantee a global optimum. Furthermore, GAs do not require any derivative information, instead relying only on the use of objective function evaluations. This point is potentially significant because obtaining such gradient information, or its approximation, is often cumbersome and expensive in many cases, especially for highly nonlinear systems such as biomechanical ones [6].

ACKNOWLEGEMENT

The authors would like to express their sincere appreciation to Dr. K.A. Khalaf from University of Miami, and Dr. P. Sparto from Universtiy of Pittsburg for providing their raw data, support, and giving their valuable comments during the preparation of this paper.

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