

A COMPUTER SIMULATION MODEL FOR PREDICTING OPTIMAL PROSTHESIS INERTIAL PARAMETERS

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INTRODUCTION

Persons with unilateral below-knee amputation face problems both with an asymmetrical gait and a higher energy cost during walking [1]. An asymmetrical gait may lead to deterioration of the knees and lumbar spine [2], and an elevated energy cost can lead to premature fatigue. Current design philosophy is to make prosthetic limbs as lightweight as possible. The considerable difference in mass and moment of inertia that exists between the intact and prosthetic limbs is likely a major cause of gait asymmetry in amputees. Increasing the mass of the prosthesis could improve gait symmetry, but might also increase energy cost. Selles et al. [3] noted these trade-off in prosthesis design, but did not report an optimal balance between these competing factors.

A simulation model that allows prosthesis inertial properties to be varied could be used as a tool to test the feasibility of restoring gait symmetry to amputees. Such a model could also potentially minimize the amount of trial-and-error testing needed in applying the current results. Therefore, the aim of this study was to utilize a computer simulation model and numerical optimization algorithm to test the feasibility of determining an inertial setup of the prosthetic limb that would restore gait symmetry, without increasing the demands of walking.

METHODS

Lower limb motion during the swing phase of walking was modeled using two rigid segments representing the thigh and combined stump/prosthesis. The hip joint was fixed in space and the two segments articulated at the knee joint. The equations of motion and corresponding Matlab code were generated using Autolev. Initial and final angles and angular velocities for the simulations were obtained from able-bodied subjects [2], but the

inertial properties of the limb segments were based on amputee subjects [1]. This arrangement allowed us to test whether the inertial properties of the prosthesis could be varied to restore normal gait symmetry, while also keeping the effort required to swing the leg low.

A simulated annealing optimization algorithm was used to determine the amount of mass that should be added to the prosthetic limb, and the location below the knee at which this mass should be added, to restore normal gait symmetry. The added mass was limited (0.0-1.7 kg) so that the prosthesis and stump mass would not exceed that of the intact limb, and the location of the added mass was limited to between the knee joint and the bottom of the foot. In addition to optimizing the mass magnitude and location, the hip and knee joint torques were optimized, using the able-bodied values [2] for the initial guess. Thus, the optimization problem was to find the added mass magnitude and location, as well as the hip and knee joint torques, that matched the final joint angles and angular velocities, while requiring the least effort. The effort required to swing the limb, used as a proxy for energy cost, was quantified as

$$effort = \int_{t_o}^{t_f} \sqrt{T_H^2 + T_K^2} dt$$

where t_o is the initial time, t_f is the final time of the swing phase, T_H is the hip torque, and T_K is the knee torque.

RESULTS AND DISCUSSION

The optimal arrangement predicted by the simulation model was to add a mass of 0.91 kg at a location of 0.28 m below the knee (i.e. below the midpoint of the shank). This added mass represents slightly greater than half of the maximum amount of mass that could be added to the prosthesis in the optimization framework. Thus, the total mass of the prosthetic limb (4.13 kg) was still lighter than the

intact limb (4.91 kg). The amount of added mass and its location shift the center of mass of the entire shank segment more distally, from 0.16 m to 0.19 m below the knee joint, and increased the moment of inertia of the shank from 0.18 kg-m² to 0.25 kg-m². The optimized values are closer to the center of mass and moment of inertia for the intact limb, 0.25 m and 0.42 kg-m², respectively.

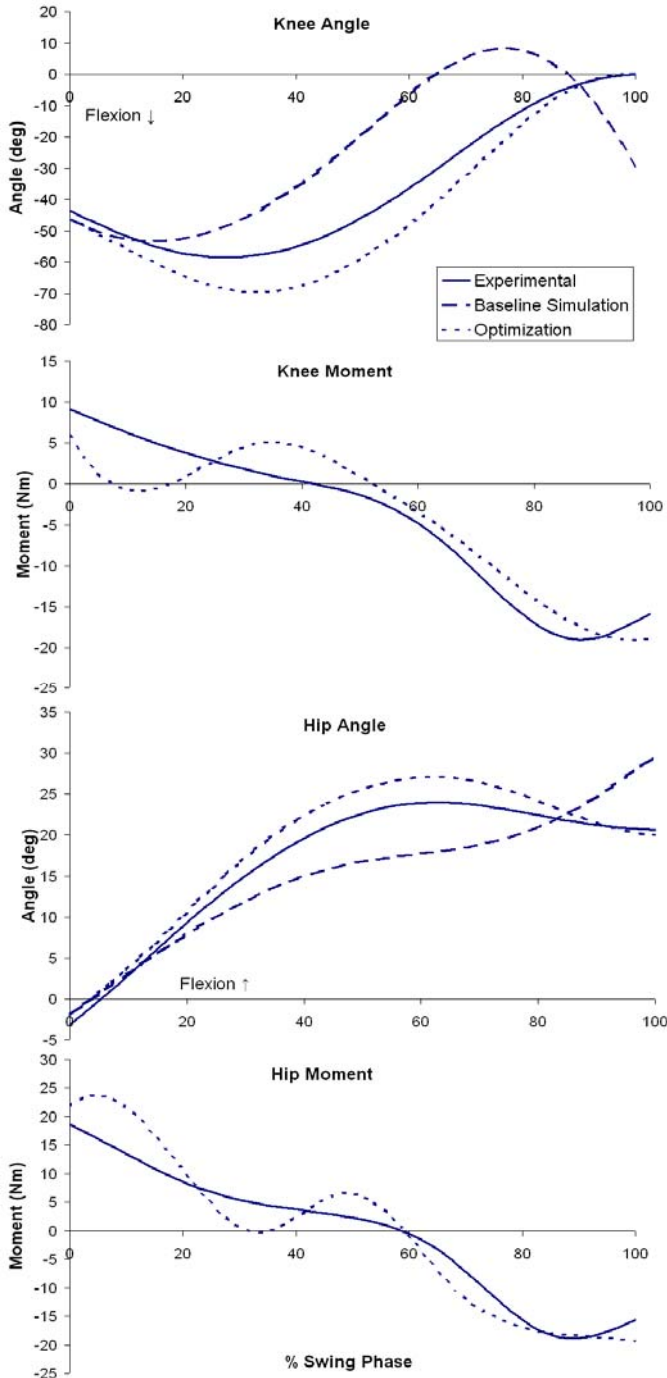


Figure 1: Graph of hip and knee angles and moments showing experimental data from a normal subject, baseline simulation results with no added mass, and optimization results with the added mass

In Figure 1, the baseline simulation without any added mass shows that the inertial characteristics of the prosthesis resulted in substantially different movements of the leg, compared to the experimental condition. Following the optimization, gait symmetry was restored and the kinematics were in good agreement with the experimental data. This was accomplished with a cost that was lower (effort = 88.2) than the value obtained from the data in able-bodied subjects [2] (effort = 104.7), indicating that near-normal leg swing can be restored, without increasing the demands of swinging the limb.

The model predictions are to increase both the mass and moment of inertia of the prosthesis, but not so much that they match the values for the intact limb. The resulting motion is returned to normal, and therefore both the effort and asymmetry are reduced by increasing moment of inertia. While this optimization suggests the optimal prosthesis set-up would be lighter than an intact limb, it still would require adding nearly 1 kg to the mass of current designs. According to prosthesis technicians and amputee patients [1], however, adding mass to a prosthetic leg is undesirable. The suggestion of adding a significant amount of mass to the leg will probably be met with great scepticism. However, it may be possible to obtain nearly as good results by placing less mass at a greater distance from the knee joint, which might be viewed more favourably.

The follow-up to this study will be empirical testing of the predictions made by the simulation model. Improvements in the model may also be called for, as a number of simplifications are currently involved. The present results may not revolutionize lower limb prosthesis designs, however, they do call for the careful consideration of mass and mass distribution to aid in the restoration of gait symmetry.

REFERENCES

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