**EFFECT OF A PROSTHETIC LIMB ON SPRINT RUNNING PERFORMANCE**

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## INTRODUCTION

Modern prosthetic devices have allowed transtibial amputee runners to reach levels of performance that approach those of able-bodied athletes. This raises the question whether these devices might provide an unfair advantage [1]. Recent studies comparing able-bodied to amputee runners have been inconclusive [2]. This will likely remain a difficult question to answer because these studies are necessarily observational and a controlled experiment can not be performed in human subjects.

Here we present a computational modeling study, in which a controlled experiment is performed to determine the effect of a prosthetic foot and ankle on maximal running speed.

## METHODS

The able-bodied musculoskeletal model used in this study is planar and consists of seven rigid body segments, trunk, 2 thighs, 2 shanks and 2 feet, actuated by 16 Hill-type muscle groups with activation and contraction dynamics [3]. Foot-ground contact was modeled by 10 elements uniformly distributed along each foot sole with nonlinear spring-damper properties and Coulomb friction at each contact point. Air drag was applied to the trunk center of mass. The model has 50 dynamic state variables $x$ and 16 controls $u$ (muscle stimulations).

The optimal control problem was formulated as: find trajectories $x(t)$, $u(t)$, and stride period $T$ to maximize speed $V$, subject to constraints due to system dynamics:

$$\dot{x} = f(x,u)$$

and periodicity:

$$x(T) = x(0) + VT\hat{x}\ ; \quad u(T) = x(0)$$

with $\hat{x}$ the state space unit vector for forward translation.

Direct Collocation was used to transform the optimal control problem into a Nonlinear Programming Problem (NLP) [4]. Bilateral symmetry was assumed. Half a gait cycle was discretized by the trapezoidal differentiation formula using 100 time nodes and the resulting NLP was solved using SNOPT (tomopt.com/tomlab). A previously optimized walking movement [5] was used as initial guess.

After optimizing the able-bodied model, all ankle muscles were removed and replaced by a torsional ankle spring (800 Nm/rad) and damper (0.35 Nms/rad) representing a typical prosthetic device for running. All ground contact points were moved to the forefoot. Mass properties were kept the same and the altered model was re-optimized to find its maximal running speed. Mechanical work rates due to muscles, prosthesis, contact, and air drag were calculated.

## RESULTS AND DISCUSSION

The able-bodied model achieved a speed of 7.45 m/s and had realistic movement and ground reaction forces. Speed was lower than elite human sprinters, possibly due to muscle model limitations. In the prosthetic condition, maximal running speed was 9.02 m/s, with much longer flight phase and higher ground reaction forces (Figure 1). The energy analysis (Table 1) showed significantly less negative and positive muscle work with the prosthesis. This was achieved mainly by a strategy that aligns the ground reaction force vector to the knee and hip joints, reducing joint moments and muscle forces. Furthermore, there was less motion in those joints, reducing muscle contraction velocity. These benefits of the prosthesis more than compensated for the loss of 95 W net work from ankle muscles (not shown), and its replacement by a net 60 W loss due to prosthesis damping.

As in all nonlinear optimizations, we can not prove that these solutions are globally optimal. We only know that no small change in control is possible that will improve performance. We can prove, however, that the able-bodied model is unable to use the strategy that was observed in the prosthetic model because the plantarflexor muscles are unable to generate this combination of force and velocity. The performance gains and extreme movement pattern predicted by this model have not been observed in actual amputee runners. It may well be that this strategy, while biomechanically feasible, is difficult to control.

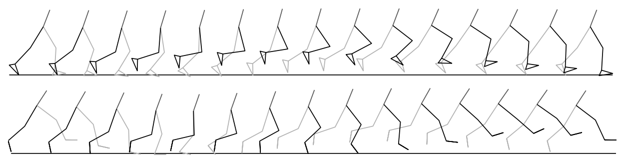

**Figure 1**: Optimal movement pattern of both models (half of the gait cycle is shown).

**Table 1:** Running performance and mechanical analysis.

| | *Able-bodied* | *Prosthetic* |
|---|---|---|
| *Running speed (m/s)* | 7.45 | 9.02 |
| *Stride period (s)* | 0.526 | 0.753 |
| *Stance phase (s)* | 0.114 | 0.111 |
| *Peak knee flexion in stance* | 51° | 47° |
| *Negative muscle work (W)* | -1376 | -324 |
| *Positive muscle work (W)* | 1653 | 654 |
| *Net prosthesis loss (W)* | 0 | -60 |
| *Net air and contact loss (W)* | -277 | -270 |

## ACKNOWLEDGEMENTS

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