Improving Below-Knee Amputee Gait
A Simulation Study of Pareto-optimal Movement Trajectories

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1 Introduction

An important goal for amputee walking is to regain a symmetric walking pattern. Below-knee amputees are often able to regain close to normal joint kinematics in the hip and knee using a prosthetic foot [1], but the joint moments are distinctly asymmetric and different from able bodied gait [1], which may contribute to a higher occurrence rate of osteoarthritis in amputees [2] and other health issues [3]. In order to reduce the asymmetry in amputee gait, and its potential negative effects, it is important to understand the causes of this asymmetry.

Asymmetry is, to some extent, inevitable because the prosthetic foot does not replicate the mechanics and control of the intact foot. However, the knee and hip of the residual limb and the entire contralateral limb, still have a complete set of muscles under voluntary neural control. We hypothesize, therefore, that below knee amputees can walk with symmetric joint moments using a passive prosthesis, but prefer not to do so because it would require additional effort or abnormal kinematics. We will test this hypothesis through predictive simulation of a dynamic musculoskeletal model.

2 Methods

Simulations were performed with a sagittal plane model having nine kinematic degrees of freedom and 16 muscles [4]. In the below-knee amputee model, Gastrocnemius, Soleus, and Tibialis Anterior were removed from the right leg and replaced by a rotational spring (600 Nm/rad) and damper (15 Nms/rad) based on [5]

Periodic open loop controls and state trajectories of a single gait cycle were found by formulating an optimal control problem, minimizing an objective function that combines tracking of normative gait data and a measure of muscular effort, as described in [4]. In the present study, a second objective was added to penalize the asymmetry in joint moments. This objective was defined as the root-mean-square difference between the joint moments in the left and right joint, with a phase shift of half a gait cycle.

The inherent asymmetry present in the legs of a below-knee amputee produces a conflict between the two objectives, and we will treat this as a multi-objective optimization problem. A Pareto-front was found by minimizing a weighted sum of the objectives, for various weight ratios. Any of the solutions on the Pareto-front can be chosen as a gait by a below knee amputee, and the hypothetical curve that connects the solutions provides insight into the tradeoff between the two objectives. Specifically, we will investigate the set of optimal solutions to see if a solution exists with more symmetric joint moments in the knee and hip that might be feasible for a below-knee amputee.

3 Results and Discussion

A baseline simulation was generated first by omitting the symmetry objective from the optimal control problem. Results are shown in Figs 2 and 3 in black as "baseline". This simulation had near-normal gait kinematics but asymmetric joint moments. Specifically, the peak knee extensor moment in the residual limb was much smaller than on the intact side, which is consistent with observations in below-knee amputees [1]. We also see a very high peak in Iliopsoas force in the residual limb at the start of the swing phase, possibly to compensate for the lack of active push off in the ankle.

By introducing the second objective (symmetric joint moments), a Pareto front (Fig. 1) was obtained, showing the trade-off between the effort/tracking objective and the moment asymmetry. Three points on the Pareto front are of special interest.

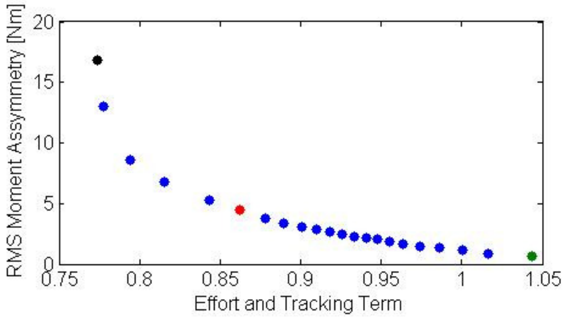

Figure 1: Pareto front of the trade-off between effort and symmetry in the joint moments.

The solution indicated by the black data point in Fig. 1 is the baseline simulation in which asymmetry in moments was not an objective. The solution indicated in red has a large improvement in joint moment symmetry, at the expense of a small increase in the tracking and effort objective. This solution is presented in detail in Fig. 2, red curves. The joint kinematics are still close to normal. The muscle force patterns changed significantly in order to achieve more symmetric moments, but the overall muscu-

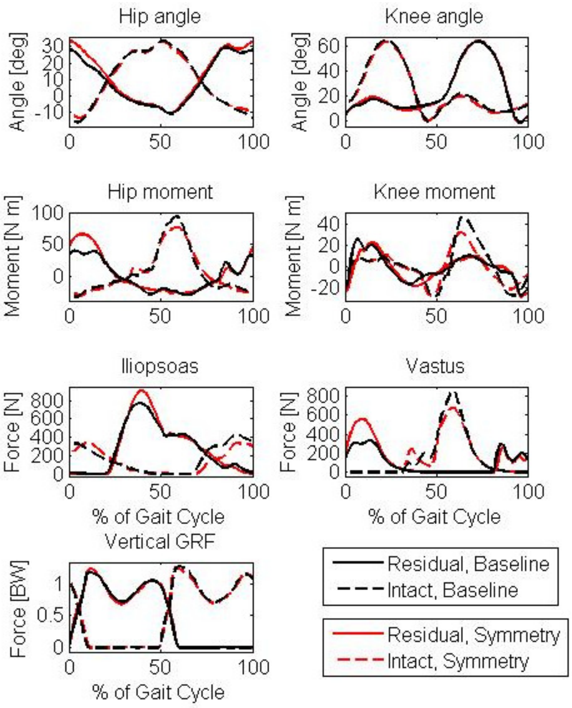

Figure 2: Joint angles, moments, Vastus and Iliopsoas muscle force and vertical ground reaction force of the baseline solution and the solution corresponding to the red dot in Fig. 1

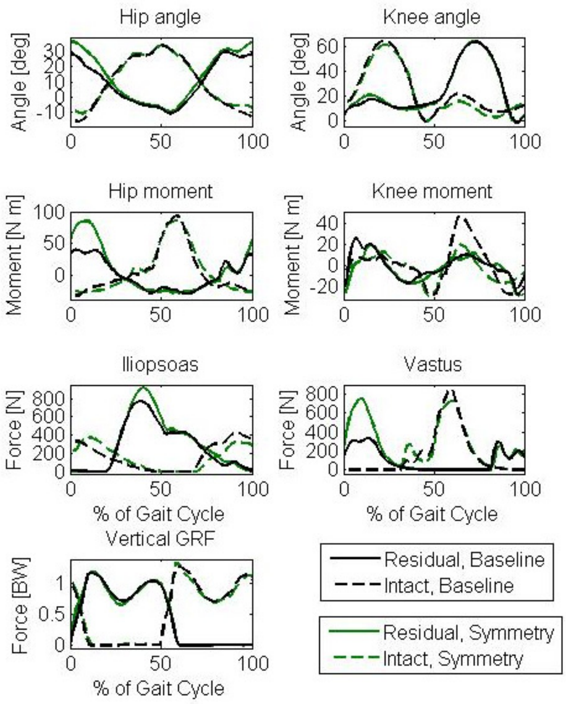

Figure 3: Joint angles, moments, Vastus and Iliopsoas muscle force and vertical ground reaction force for the baseline solution and the solution depicted by the green dot in Fig. 1

lar effort hardly changed from the baseline conditions. Symmetry in the Vastus increased, while asymmetry in the Iliopsoas increased, unexpectedly, but the contribution of hip flexor moment to the symmetry objective is small, relative to that of the hip extensor moment.

The third solution (indicated in green in Figs 1 and 3) shows that it is not desirable to put too much emphasis in symmetric joint moments. The peak hip extensor moment in the residual limb has now risen to 86 [Nm], compared to 77 [Nm] in the solution depicted by the red dot and 44 [Nm] in able-bodied gait. This would correspond to higher compressive loads in the hip joint. One can also see that the vertical ground reaction force in the intact leg is higher in this solution, which might increase the joint reaction forces in all joints. Furthermore, the effort increased by 8%, causing the amputee to fatigue more quickly when choosing this strategy.

4 Conclusion

The hypothesis that below-knee amputees are able to walk with symmetric joint moments was confirmed. The peak knee and hip extension moments in the intact leg could be reduced significantly at the cost of a small increase in tracking error and effort. This could potentially reduce the occurrence rate of osteoarthritis in below-knee amputees.

It should be verified using a subject study if below-knee amputees can achieve the reported gait with more symmetric joint moments. Also, the use of the predictive simulation framework can be expanded by adding a motor to the prosthetic system. The motor control parameters can be optimized to provide positive work during push-off and decrease the peak Iliopsoas force. Finally, a training program could be designed to teach below-knee amputees to walk with more symmetric joint moments.

References

[1] Ventura, J. D., G. K. Klute, and R. R. Neptune. "The effects of prosthetic ankle dorsiflexion and energy return on below-knee amputee leg loading." *Clinical Biomechanics* 26.3 (2011): 298-303.
[2] Lemaire, E. D., and Fisher F. R. “Osteoarthritis and elderly gait.” *Arch. Phys. Med. Rehabil.* 75 (1994): 1094-1099.
[3] Ephraim, Patti L., et al. "Phantom pain, residual limb pain, and back pain in amputees: results of a national survey." *Arch. Phys. Med. Rehabil.* 86.10 (2005): 1910-1919.
[4] Van den Bogert, A. J., et al. "Predictive musculoskeletal simulation using optimal control: effects of added limb mass on energy cost and kinematics of walking and running." *Proc Inst Mech Eng, P: J Sports Eng Technol* 226.2 (2012): 123-133.
[5] Zmitrewicz, Robert J., et al. "Mechanical energetic contributions from individual muscles and elastic prosthetic feet during symmetric unilateral transtibial amputee walking: a theoretical study." *J Biomech* 40.8 (2007): 1824-1831.