A Predictive Simulation Study into the Effect of Below-Knee Prosthesis Alignment on Metabolic Cost

Anne D. Koelewijn[1,2], Marlies Nitschke[1], Antonie van den Bogert[2]
[1]Machine Learning and Data Analytics Lab, Faculty of Engineering, Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany
[2]Parker Hannifin Laboratory for Human Motion and Control, Department of Mechanical Engineering, Cleveland State University, Cleveland, Ohio, USA
Email: anne.koelewijn@fau.de

Summary

We investigated the effect of below-knee prosthesis alignment on metabolic cost in simulation. Metabolic cost was reduced when the prosthesis was abducted or externally rotated, though not significantly. Further research should investigate how joint reaction forces are affected by prosthesis alignment.

Introduction

Metabolic energy expenditure and joint reaction forces are important gait variables when evaluating a prosthesis. Many studies have evaluated their relation to prosthesis stiffness (e.g. [1]), but little research has investigated how these variables are affected by prosthesis alignment. Prostheses fit depends on the experience of the prosthetist [2]. When a prosthesis is misaligned, the loading of the legs changes [2], which likely affects metabolic cost and joint loading.

Previous work has shown that a sagittal plane alignment change of a below-knee prosthesis increases metabolic cost [3], but no such study investigated transverse and frontal plane alignments changes. A predictive simulation study could provide insight into metabolic cost and joint loading without requiring a costly and time-consuming experiment. Therefore, we compared predictive gait simulations with different below-knee prosthesis alignments to investigate how an alignment change affects joint loading and metabolic cost.

Methods

Predictive simulations were generated using the approach described in [4]. The below-knee prosthesis was modeled as a rotational ankle spring with a stiffness of 600 Nm/rad and a damping ratio of 15 Nms/rad [5]. The reference alignment was the original model alignment. The prosthesis alignment was then changed by introducing 5 and 10 degree offsets between the femur and the prosthesis in flexion, extension, abduction, adduction, and internal and external rotation.

Trajectory optimization problems were solved to simulate gait with all prosthesis alignments. Muscle stimulations were found to create a periodic gait trajectory while minimizing muscular effort and tracking normal gait data [6]. 50 virtual participants were drawn with a random mass, body mass index, isometric muscle force, optimal contractile element length, and maximum shortening velocity. Tendon slack length was adjusted to not change the total muscle length.

Results and Discussion

5 virtual participants were discarded since an unrealistic local optimum was found for at least one alignment. An ANOVA test found statistically significant differences ($p < 0.0001$) in metabolic cost, calculated using Umberger's model [7], between alignments (table 1). A multiple comparisons test showed that only the 10-degree flexion alignment was significantly different from the reference. Similar to [3], metabolic cost increased with a sagittal alignment change. Metabolic cost was reduced 1% with a 10-degree abduction or external rotation alignment. Even such a small difference might be beneficial to persons with a transtibial amputation.

We also found that alignment changed joint moments and muscle activations. Therefore, joint reaction forces are likely altered as well. These changes were small for the external rotation, indicating that the energy expenditure reduction requires only small loading changes. Further analysis should identify any favorable changes in joint loading.

Conclusions

We conclude that metabolic cost is not significantly altered by prosthesis alignment, though small reductions might be achieved. Kinetic results suggest that joint reaction forces are altered. Further analysis of joint reaction forces is required to completely understand the effect of prosthesis alignment.

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Table 1: Average metabolic cost of predictive simulations over 45 virtual participants with different prosthesis alignments.

Alignment	Reference	Flexion		Extension		Abduction		Adduction		Internal Rotation		External Rotation	
Offset in degrees		5	10	5	10	5	10	5	10	5	10	5	10
Metabolic Cost (J/kg/m)	3.03	3.06	3.11	3.04	3.04	3.02	2.99	3.05	3.06	3.04	3.04	3.02	3.00