Optimizing a Passive Hip Exoskeleton for Balance on a Prosthetic Foot

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Summary

Use of passive exoskeletons to tune muscle-tendon dynamics for improvement of balance remains an unexplored area of research. A computational model of standing balance on a passive prosthesis was used to find values of hip exoskeleton stiffness and damping which optimized resistance to destabilizing lateral perturbations. Unexpectedly, optimum exoskeleton stiffness and damping were dependent on prosthesis stiffness, and did not tune hip muscle-tendon units for maximum dissipation of the destabilizing impulse.

Introduction

About 50% of people with lower limb loss (LLL) fall each year [1]. The inability to balance for >5 seconds on one limb has been identified as a predictor of injurious falls [2]. This is concerning given that people with LLL can rarely achieve this task on their spring-like prosthetic feet. Lateral balance, which is critical for avoiding falls, is achieved through ankle, hip, and stepping strategies [3]. For individuals with LLL, improving the ability of hip musculature to dissipate perturbations may lower fall risk and improve quality of life. We hypothesized that an optimal passive hip exoskeleton for improving balance would consist of a pure damper (vs. a spring or spring-damper combination), and that optimal exoskeleton parameters would maximize energy dissipation/absorption by hip muscle-tendon units.

Methods

A computational model of prosthetic limb balance in the frontal plane was devised, consisting of two rigid bodies (a lumped head, arms, and trunk segment, and a lumped leg segment), a pin joint at the hip, and a torsional spring connecting the leg to the ground (a passive prosthetic foot). Hill-type muscle-tendon units actuated the hip joint. Stretch reflexes stimulated the hip musculature. A torsional spring and damper at the hip joint represented a passive hip exoskeleton (Figure 1L). For all combinations of exoskeleton stiffness (0-100 Nm/rad), exoskeleton damping (0-50 Nms/rad), and prosthesis stiffness (500-750 Nm/rad), the model was destabilized with progressively larger lateral impulsive forces (pushes) delivered to the hip joint over 0.5 msec. The smallest push which caused toppling in <5 sec was considered the critical push magnitude for a fall.

Energy dissipation/absorption by biological and exoskeletal hip components was quantified using the negative work of the muscle-tendon units and the hip exoskeleton, respectively.

Results and Discussion

The optimal exoskeleton parameters exhibited a dependence on prosthesis stiffness: more compliant prostheses required higher exoskeleton damping and no stiffness, while stiffer prostheses required both higher exoskeleton damping and stiffness. Optimal hip exoskeletons increased the critical perturbation for failure between 3.9 and 20.2% relative to conditions with no exoskeleton (Table 1). Optimal exoskeleton parameters did not maximize energy dissipation/absorption by hip muscle-tendon units (Figure 1R), but instead provided optimal shuttling of impulsive energy between ankle and hip to prevent toppling.

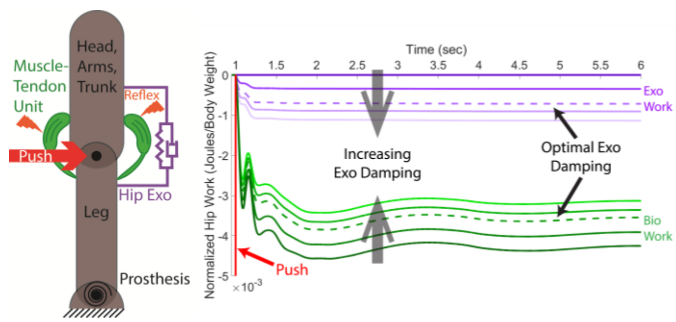

Figure 1: L – Frontal plane prosthesis balance model. R – For a 600 Nm/rad prosthesis, the optimum damping did not result in the most negative biological hip work.

Conclusions

Contrary to our hypotheses, optimal hip exoskeleton properties were dependent on prosthetic stiffness and were not exclusively dampers. Further, optimized exoskeletons did not optimize energy dissipation by hip musculature but rather tuned inter-joint energy transfers.

References

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Table 1: Optimal hip exoskeleton properties at each prosthetic foot stiffness

Prosthesis Stiffness (Nm/rad)	500	550	600	650	700	750
Optimal Exo Stiffness; Damping	0 Nm/rad; 28.67 Nms/rad	0 Nm/rad; 4.15 Nms/rad	0 Nm/rad; 2.26 Nms/rad	0.03 Nm/rad; 4.33 Nms/rad	2.56 Nm/rad; 6.35 Nms/rad	6.28 Nm/rad; 8.42 Nms/rad
Critical Push Magnitude for a Fall (% of No Exo Condition)	9.2%	3.9%	5.3%	12.3%	15.4%	20.2%