Whole-leg exoskeleton assistance halves the metabolic cost of walking on inclines

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I. Background

For exoskeletons to be successful as mobile devices, they will need to be effective across a variety of terrains, including on inclines. Exoskeletons may be well-suited to assist incline walking because steeper inclines incur higher metabolic costs than level ground and require larger biological torques. While some exoskeletons have assisted incline walking as shown by reductions in metabolic cost [1], recent level-ground assistance successes indicate greater improvements are possible by assisting the whole-leg [2]. It is also unknown how optimal assistance on inclines differs from level-ground, or how it changes across different slopes. To understand how effective assistance on inclines can be and how assistance should change with incline, we used human-in-the-loop optimization to find whole-leg exoskeleton assistance profiles that minimize the metabolic cost of walking on a range of walking inclines.

II. Methods

Three expert, able-bodied participants walked in a hip-knee-ankle exoskeleton [3] on level-ground, 5 degree, 10 degree and 15 degree inclines. We used human-in-the-loop optimization to find whole-leg exoskeleton torques that minimized measured metabolic cost, similar to [2], [4]. We also measured applied torques, kinematics, and muscle activity. Participants walked at slower speeds for steeper inclines, so we calculated the cost of transport to isolate the effect of inclines.

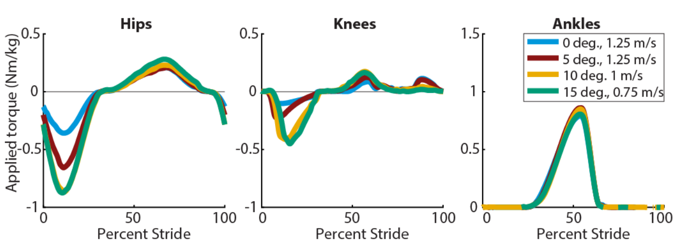

Fig. 1. Optimized exoskeleton assistance for each condition averaged across participants. For conditions 10 degrees and steeper, hip extension and knee extension approached maximum allowed torque based on comfort limits. Peak ankle plantarflexion torque was the maximum allowed for almost every condition.

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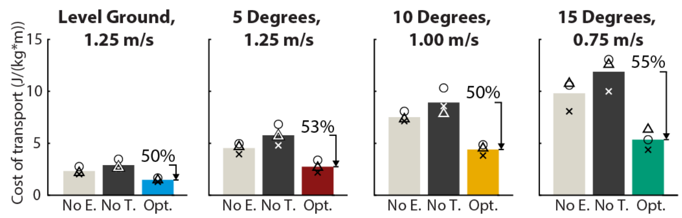

Fig. 2. Cost of transport (J / (kg*m)) for each condition (no exoskeleton: gray, no torque: black, optimized assistance: color).

III. Results and Discussion

For all assistance conditions, cost of transport was reduced by at least 50% relative to walking in the device with no assistance, a large improvement to walking consistent with level-ground reductions. This corresponds to large absolute reductions in metabolic cost, with the most strenuous conditions reduced by around 5 W/kg. Optimized extension torques increased as incline increased, with hip extension, knee extension, and ankle plantarflexion torques growing as large as allowed by comfort-based limits. We will study user kinematics, muscle activity, and power to investigate the biomechanics underlying these findings.

IV. Conclusion

Future exoskeleton devices can expect to deliver large improvements to walking across a range of inclines if they are able to apply large assistance torques and powers.

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References

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