For an Exo to Be, as Good as Can Be, Help the Ankle, the Knee, the Hip or All Three?

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I. Introduction

It is well known that exoskeletons can reduce the metabolic cost of walking, but what are the best ways to do so and what are the limits? For example, is it better to assist the hip or the ankle joint? Both joints are associated with a large portion of normal energy use [1] and assistance at each has yielded large improvements [2], but direct comparisons have yet to be made. A related question is: can knee-only assistance reduce metabolic cost? Knee musculature consumes significant energy [1], but assistance at this joint has yet to be effective during level walking. Even more interestingly, if we assist all three joints simultaneously, will the benefits be greater than the sum of their parts? The benefits might be greater, because coupled exoskeleton assistance can offload bi-articular musculature [3]. The benefits might be lesser, because assistance at one joint may already indirectly assist muscles at other joints [4]. And when assisting all joints simultaneously in the sagittal plane, how close can we come to completely eliminating the metabolic cost of walking? We can expect that some energy will be required for frontal and transverse functions, and perhaps for baseline muscle activity related to balance, but how much is unknown.

II. Methods

We used a hip-knee-ankle exoskeleton emulator to conduct human-in-the-loop optimization of exoskeleton torque to minimize measured metabolic cost in a manner similar to [5]. We have completed collections for one participant (M, 90 kg) with two more participants enrolled.

III. Results and Discussion

Hip-only and ankle-only assistance both reduced the metabolic cost of walking by about 30% (Fig. 1D), confirming that both joints are good targets for assistance. Knee-only assistance reduced the cost of walking by 18%, demonstrating that effective knee assistance is indeed possible. Multi-joint assistance reduced the cost of walking by 51%, the largest improvement to date, showing that at least half of the metabolic energy expended during walking can be saved

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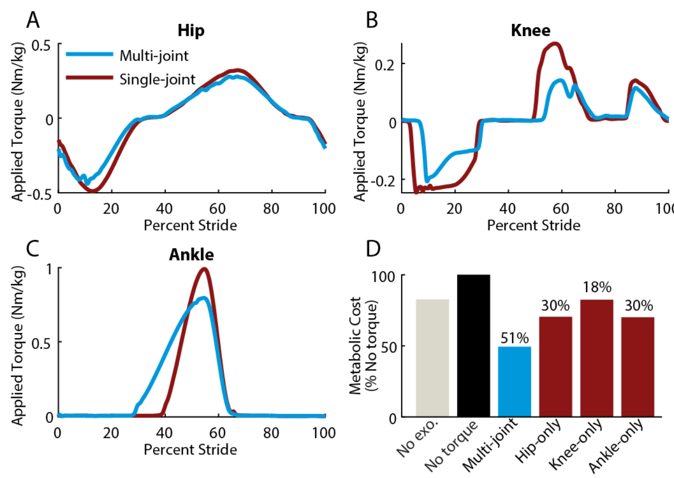

Fig. 1. Optimized assistance torques for single-joint (red) and multi-joint (blue) for the hip (**A**), knee (**B**), and ankle (**C**). Metabolic cost of walking (**D**) as a percentage of walking in the exoskeleton with no torque (black) for multi-joint assistance (blue) and each single-joint assistance (red). Metabolic cost of walking is calculated by subtracting out the cost of quiet standing. For each assistance, percent reduction relative to no torque is shown.

through exoskeleton assistance. It remains to be seen whether this limit could be exceeded by assisting additional joint functions, such as hip abduction, or aiding balance. The total energy cost reduction was smaller than the sum of its parts (78%), consistent with the idea that optimal single-joint assistance derives a substantial portion of its benefit from indirectly assisting musculature at other joints. This idea is also consistent with the observation that peak torque was lower with multi-joint assistance than single-joint assistance after all of these patterns were optimized (Fig. 1A-C).

Designers of exoskeletons can reduce the metabolic cost of walking by assisting any lower-limb joint in the sagittal plane, but the hip and ankle are the best single joints, and, at least when it comes to energy, all three is better, substantially.

References

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