Hip, Knee, Ankle and Multi-Joint Exoskeleton Assistance Can Reduce Metabolic Cost

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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.

Methods

We used a hip-knee-ankle exoskeleton emulator to conduct human-in-the-loop optimization of exoskeleton torque to minimize measured metabolic cost of walking in a manner similar to [5]. Muscle activity was measured using surface electromyography in a manner similar to [6]. Three participants (2M 1F, 61-90 kg) completed the protocol.

Results and Discussion

Hip-only and ankle-only assistance reduced the metabolic cost of walking by about 26% and 30% respectively (Fig. 1), confirming that both joints are good targets for assistance. Knee-only assistance reduced the cost of walking by 13%, demonstrating that effective knee assistance is indeed possible.

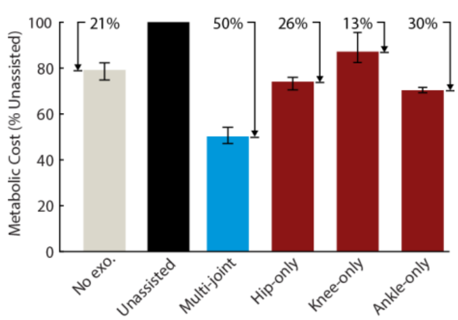

Figure 1: Metabolic cost of walking as a percentage of walking in the exoskeleton with no torque (black) for multi-joint assistance (blue) and each single-joint assistance (red), with bars as mean over three participants and range indicated by whiskers. Metabolic cost of walking is calculated by subtracting out the cost of quiet standing. For each assistance, percent reduction relative to no torque is shown.

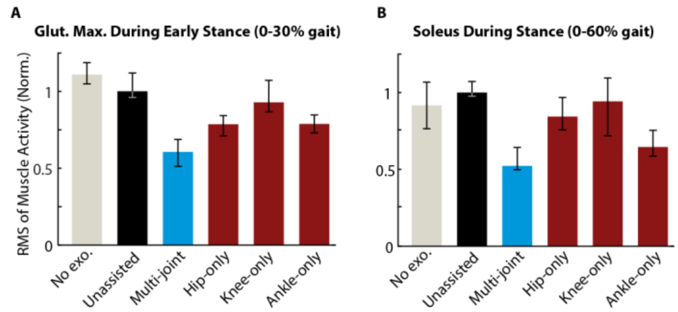

Figure 2: Normalized root-mean-square (RMS) of measured muscle activity for walking without the exoskeleton (gray), in the exoskeleton with no torque (black), with multi-joint assistance (blue) and with each single-joint assistance (red), with bars as mean value and whiskers indicating range. Muscle activity was analyzed for the gluteus maximus (**A**) during early stance, estimated as 0-30% gait, when it is expected to be active, and for the soleus (**B**) during stance, estimated as 0-60% gait.

Multi-joint assistance reduced the cost of walking by 50%, the largest improvement to date, showing that at least half of the metabolic energy expended during walking can be saved 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 (69%), consistent with the idea that optimal single-joint assistance derives a substantial portion of its benefit from indirectly assisting musculature at other joints. This is supported by the muscle activity of the gluteus maximus (Fig. 2A); activity decreased for hip-only and multi-joint assistance as expected, but also decreased during ankle-only assistance, indicating that the gluteus was indirectly assisted by ankle exoskeleton torque. This effect was less pronounced for the soleus (Fig. 2B), where hip-only assistance only slightly reduced muscle activity.

Significance

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.

Acknowledgments

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