Optimized Hip-Knee-Ankle Exoskeleton Assistance Reduces the Metabolic Cost of Walking With Worn Loads

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Research

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Abstract

Background

Load carriage is a typical activity in a wide range of professions, but prolonged load carriage is associated with increased fatigue and overuse injuries. Exoskeletons could improve the quality of life of these professionals by reducing metabolic cost to combat fatigue and reducing muscle activity to prevent injuries. Current exoskeletons have reduced the metabolic cost of loaded walking by up to 23% when assisting one or two joints. Greater metabolic reductions may be possible with optimized assistance of the entire leg.

Methods

We used human-in the-loop optimization to optimize hip-knee-ankle exoskeleton assistance with no additional load, a light load (15% of body weight), and a heavy load (30% of body weight) for three participants. All loads were applied through a weight vest with an attached waist belt. We measured metabolic cost, exoskeleton assistance, kinematics, and muscle activity. We performed one-tailed paired t-tests to determine significant reductions for metabolic cost and muscle activity, and we performed an analysis of variance (ANOVA) to determine significant changes across load conditions for metabolic cost and applied power.

Results

Exoskeleton assistance reduced the metabolic cost of walking relative to walking in the device without assistance for all tested conditions. Exoskeleton assistance reduced the metabolic cost of walking by 47% with no load ($p = 0.02$), 35% with the light load ($p = 0.03$), and 43% with the heavy load ($p = 0.02$). The smaller metabolic reduction with the light load may be due to insufficient participant training or lack of optimizer convergence. The total applied positive power was similar for all tested conditions, and the positive knee power decreased slightly as load increased. Optimized torque timing parameters were consistent across participants and load conditions while optimized magnitude parameters varied.

Conclusions

Whole-leg exoskeleton assistance can reduce the metabolic cost of walking while carrying a range of loads. The consistent optimized timing parameters suggest that metabolic cost reductions are sensitive to torque timing. The variable torque magnitude parameters could imply that torque magnitude should be customized to the individual, or that there is a range of useful torque magnitudes. Future work should test whether applying the load to the exoskeleton rather than the person's torso results in larger benefits.

Full Text

This preprint is available for download as a PDF.

Figures

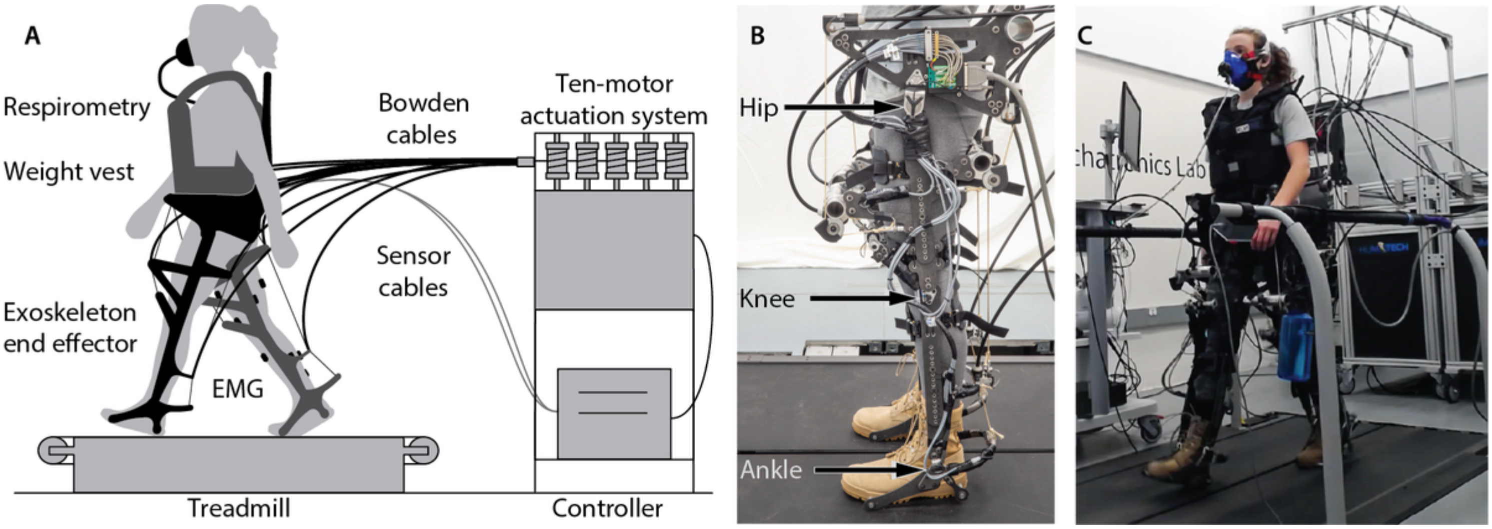

Figure 1

Experimental setup. (A) exoskeleton emulator system. A participant wears the hip-knee-ankle exoskeleton emulator and walks on a split-belt treadmill. Powerful, offboard motors apply joint torques through a Bowden cable transmission. (B) exoskeleton end effector. The device can assist the hips, knees, and ankles. (C) experimental setup. Metabolic rate and muscle activity are measured while a participant wears the exoskeleton end effector and walks on a split-belt treadmill.

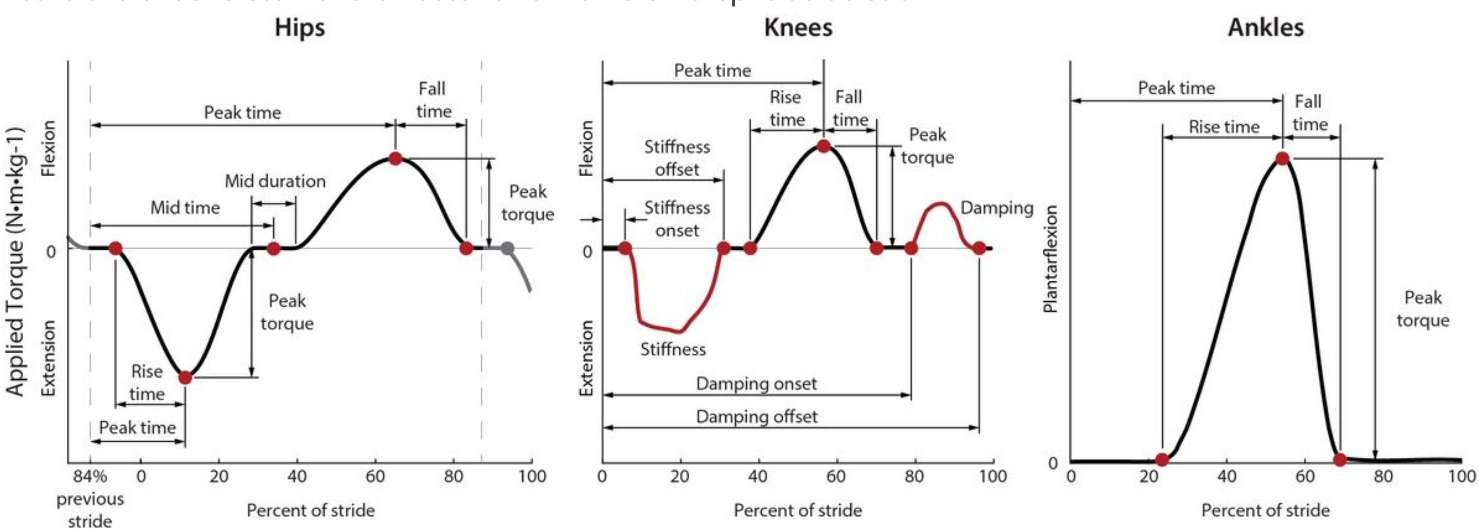

Figure 2

Parameterization of the hip, knee, and ankle torque profiles. Torque is defined as a function of stride time with periods of state-based torque at the knees. Hip assistance is defined by 8 parameters, knee assistance by 10 parameters, and ankle assistance by 4 parameters for a total of 22 parameters. The optimization algorithm can adjust the labeled nodes or state variables (red). The hip stride time is reset at 84% of stride to avoid discontinuities in the desired torque prole during heel strike.

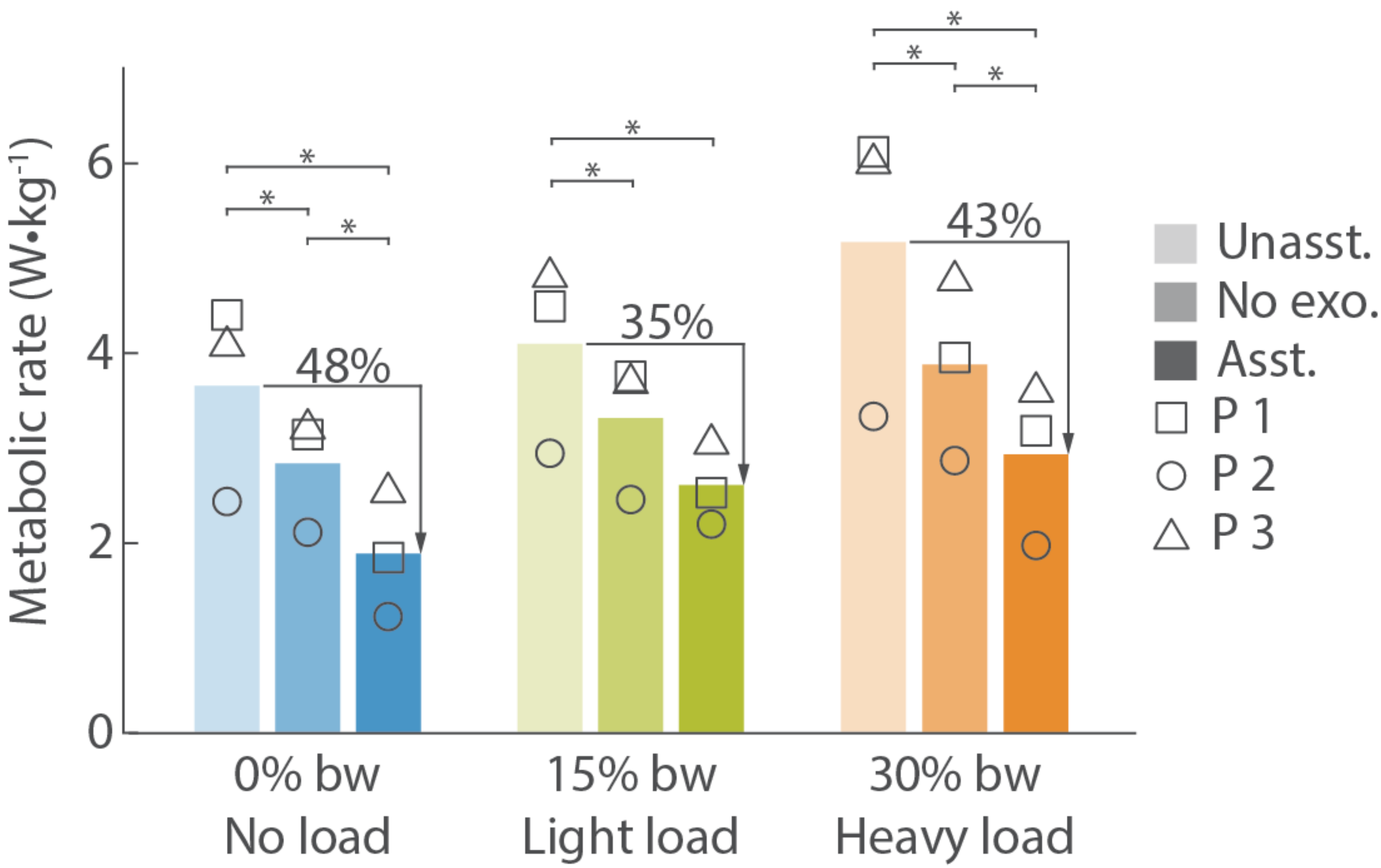

Figure 3

Metabolic cost of walking. The metabolic cost of unassisted walking (Unasst.), walking without the device (No exo.), and assisted walking (Asst.) with no load (blue), light load (green) and heavy load (orange). Individual metabolic scores are shown with symbols (p1 □, p2 O, p3 4). Exoskeleton assistance significantly reduced the metabolic cost of walking relative to the unassisted condition for all three loads and relative to the no device condition for the no-load and heavy load conditions. Quiet standing has been subtracted from all costs.

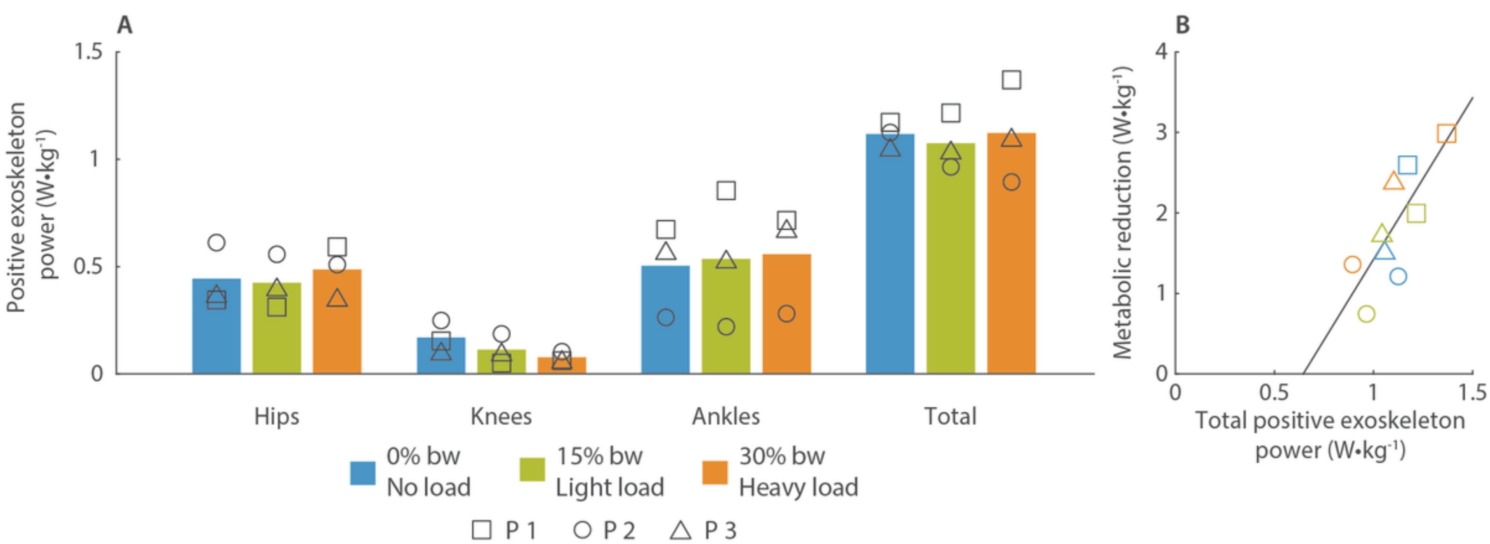

Figure 4

Exoskeleton positive power. (A) positive exoskeleton power at the hips, knees, ankles and the whole leg. The joint power was summed between the left and right legs for each joint, and the total power is the sum of the joint powers. The results for no load (blue), light load (green) and heavy load (orange) are shown, and the results for each participant are shown with symbols (p1 , p2 O, p3 Δ). (B) the metabolic rate compared to the positive exoskeleton power. Power applied to each participant is shown with symbols (p1 , p2 O, p3 4), and the colors represent the load conditions (blue for no load, green for light load, and orange for heavy load). The data was t with a line (Metabolicreduction = 4:01P+ exo - 2:59;R2 = 0:61).

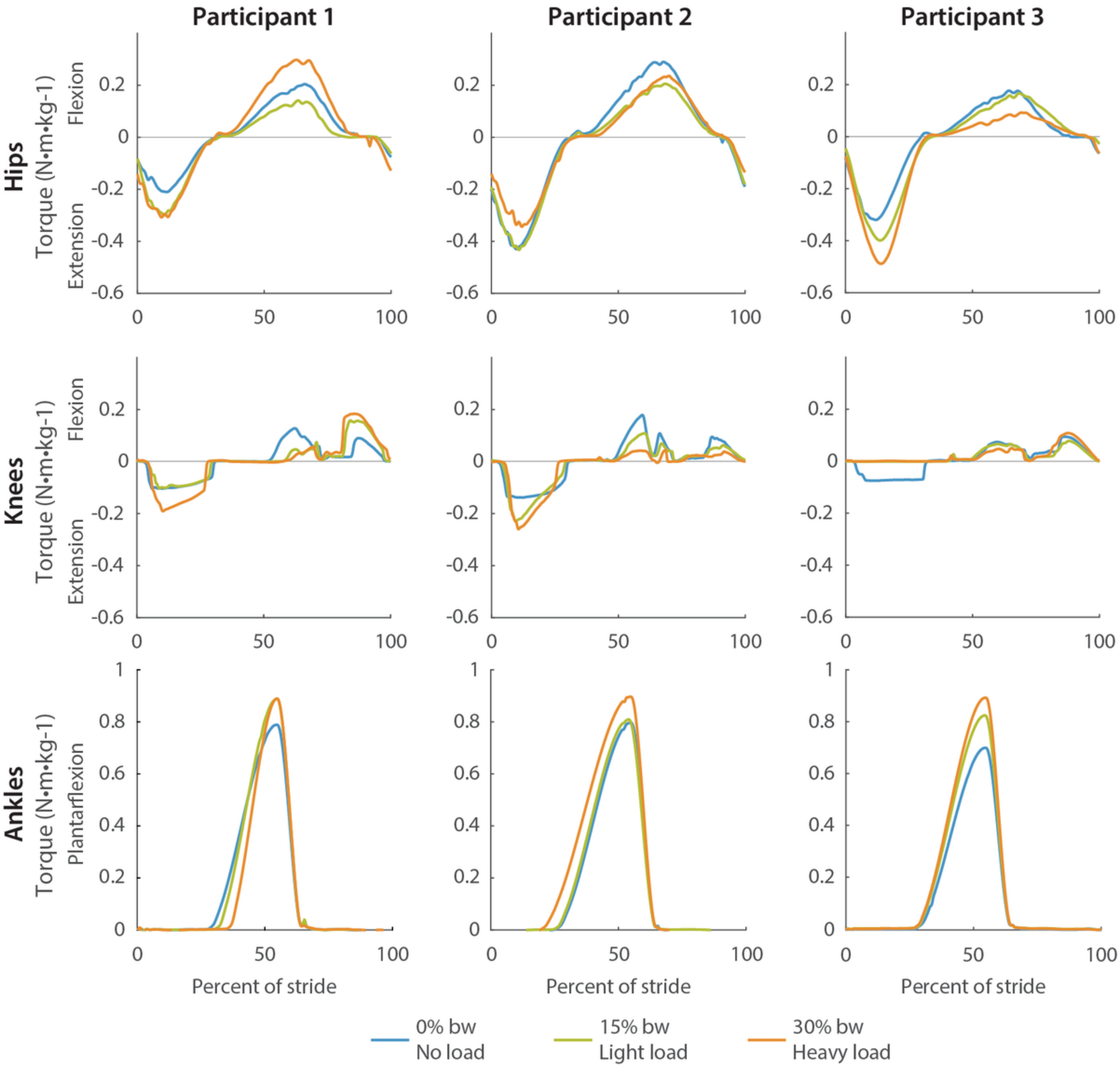

Figure 5

Optimized hip, knee and ankle torque profiles for each participant. The optimized torque profiles with no load (blue), light load (green), and heavy load (orange) are plotted as a percent of stride. Ankle torque magnitude was the smallest for the no-load condition and largest for the heavy load condition for all three participants. Optimized hip and knee torque magnitudes varied for each participant. Most timing parameters were similar across loads and participants.

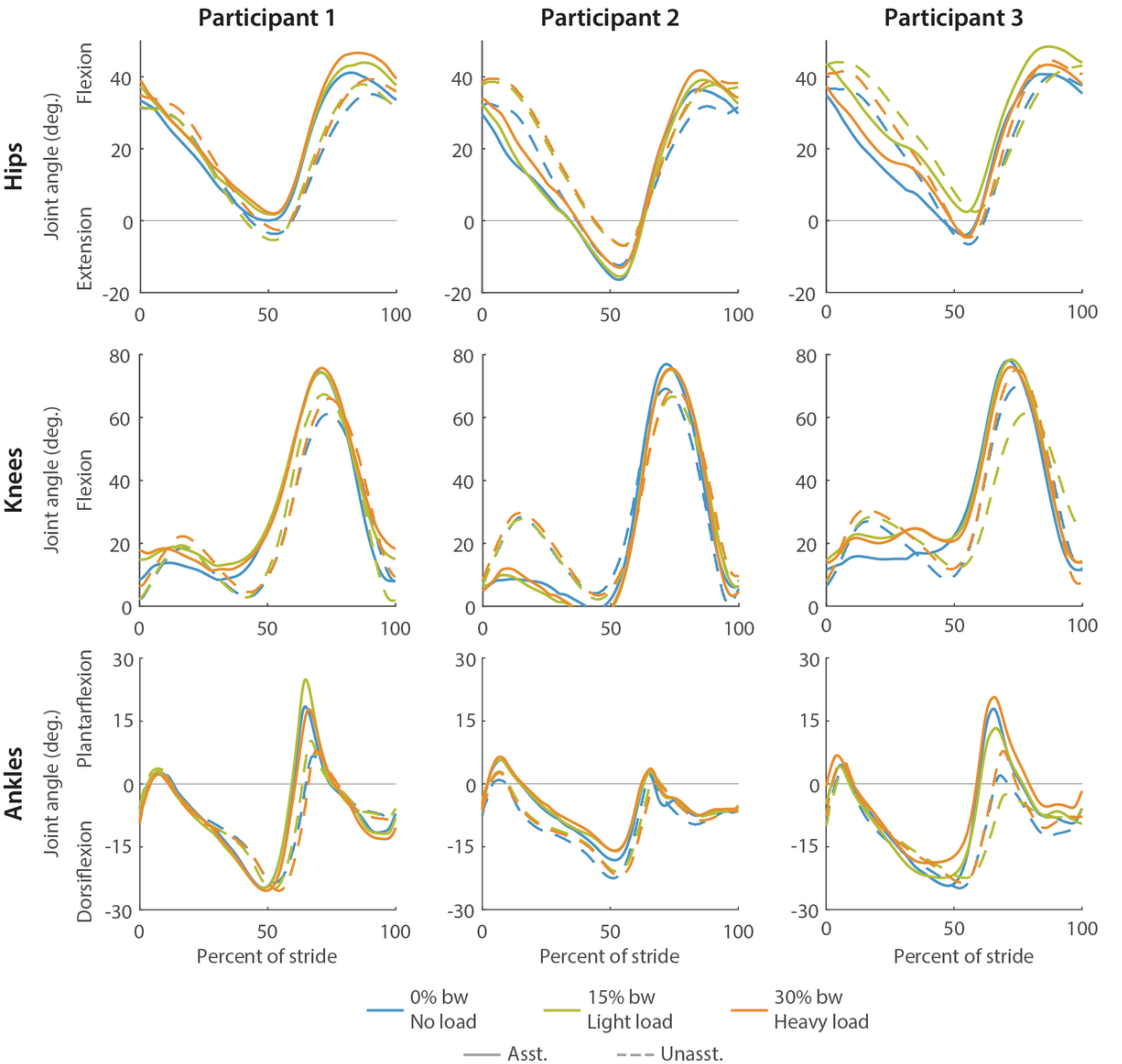

Figure 6

Average hip, knee and ankle joint angle trajectories for each participant. Assisted (solid) and unassisted (dashed) joint angle trajectories are shown for the no-load (blue), light load (green), and heavy load (orange) conditions. Joint angle trajectories changed slightly with load typically in the direction of exoskeleton assistance.

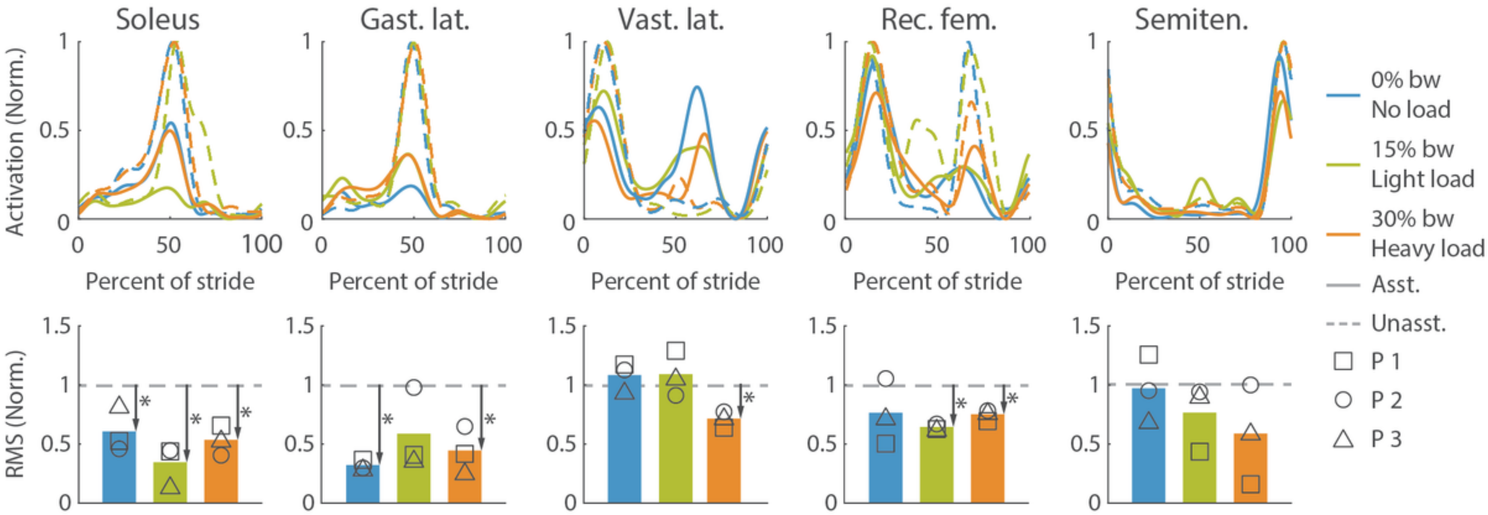

Figure 7

Average muscle activity profile over a stride (top row) and RMS of muscle activity (bottom row). The top row shows the averaged unassisted (dashed) muscle activity prole over a stride and the assisted (solid) no load (blue), light load (green) and heavy load (orange) conditions. The bottom row shows the RMS of the muscle activity with assistance for all load conditions. The RMS of the unassisted muscle activity is shown with the gray line (dashed). Muscle activity was normalized to the unassisted activity resulting in a peak value of 1 for unassisted walking at all loads.

Supplementary Files

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- Supplementary.pdf