Prosthetic ankle push-off work reduces metabolic rate but not collision work in non-amputee walking

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Supplementary Information

Candidate mechanical correlates of metabolic rate

Simple dynamic models of walking are often optimized for energy consumption, with results proposed as predictive of human behavior under similar circumstances. These models often use some measure of mechanical work as a proxy for metabolic energy consumed by muscles, but there are many candidate work values to minimize. We compared the observed changes in metabolic energy consumption across conditions to three candidate correlative models: prosthesis work, center of mass work, and joint work (Fig. 1). The Prosthesis model represents the case that prosthesis work directly replaces muscle fascicle work, and predicts changes in metabolic rate that are about twice as large as those measured for high values of push-off work. The Center of Mass model represents the case that the biological component of mechanical work done by the legs on the center of mass of the body is indicative of muscle fascicle work, and predicts changes in metabolic rate that are about half as large as those measured. The Joint work model represents the case that the sum of mechanical work done across all the joints is indicative of muscle fascicle work, and predicts similar changes in metabolic rate to those observed. In each case, we assumed an efficiency of 25% for producing positive work and -120% for absorbing negative work.

Supporting energetics and mechanics figures

Trends in metabolic rate for individual subjects are reported in Fig. 2. Changes in contralateral-limb ground reaction forces during double support led to reduced knee adduction torque in the intact-side knee (Fig. 3), which is thought to be beneficial in reducing risk of developing osteoarthritis. Joint angle, torque and power for the ankle, knee, and hip joints on the intact (Fig. 4) and prosthesis (Fig. 5) side legs are also provided for

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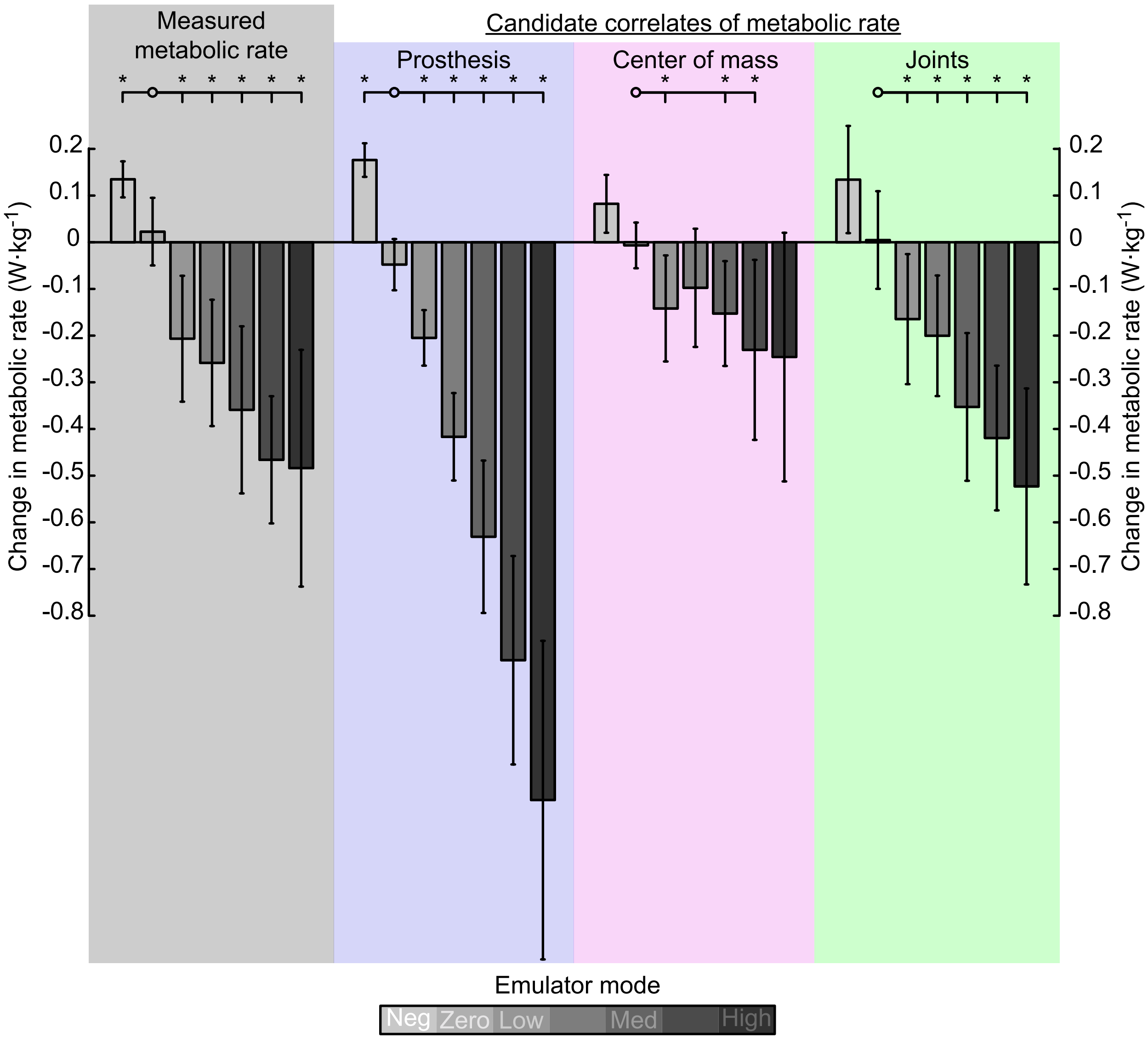
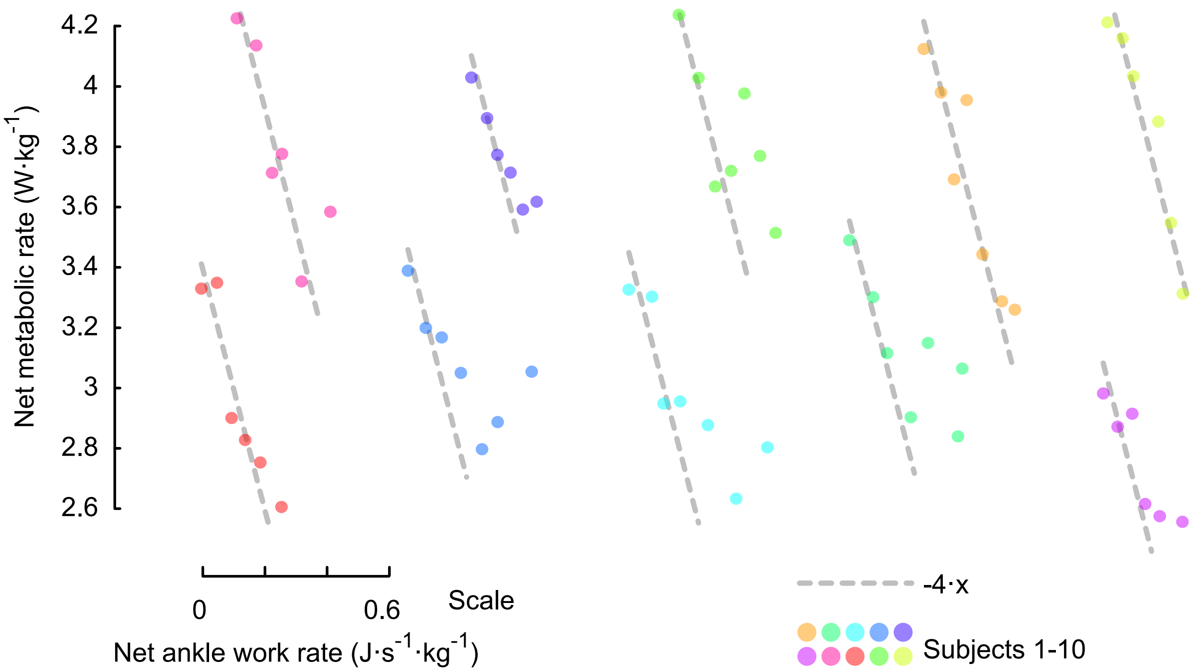
reference. Kinetic and potential energies of the whole prosthesis-side limb, contralateral limb, and the rest of body (assumes torso, head, arms, etc. are a lumped mass at pelvis) as trajectories (Fig. 7) and change in energy across the period of prosthetic ankle push-off (Fig. 8).

Temporal symmetry

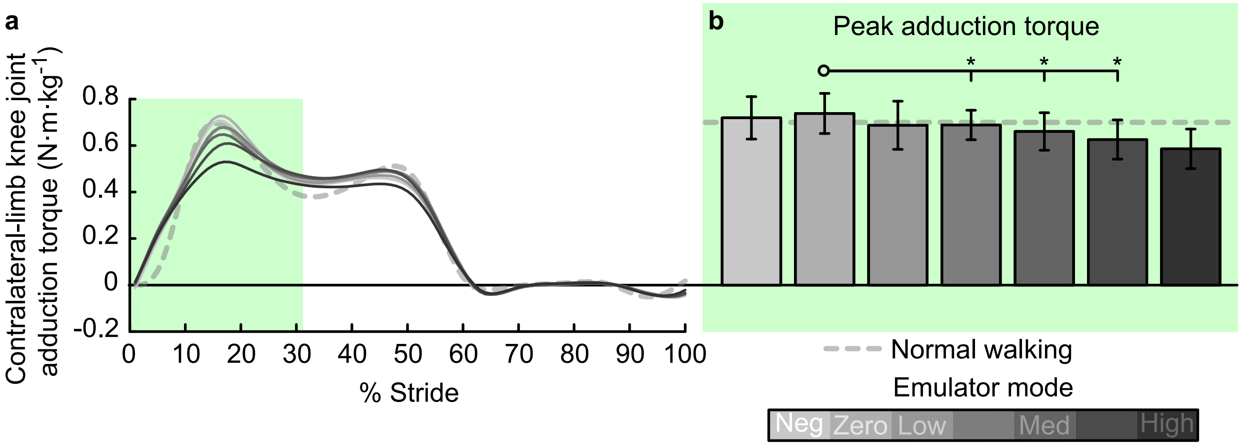
Healthy humans tend to walk with symmetric gait, and gait symmetry is sometimes suggested as a goal for gait rehabilitation. Disabilities like amputation can create physiological asymmetries, however, so it is not clear that adapting a symmetric gait is always optimal. We measured temporal gait asymmetry across conditions, defined as $Assym = (T_{ps} - T_{is})/(T_{ps} + T_{is})$, where T_{ps} is the time between prosthetic heel strike and intact heel strike and T_{is} is the time between intact heel strike and prosthetic heel strike. Temporal symmetry was significantly affected by prosthesis push-off work ($\mathrm{P} = 7 \cdot 10^{-5}$, Fig. 6). Asymmetry was minimized in the Medium prosthesis work condition, whereas metabolic energy expenditure was minimized for the High work condiiton. These results demonstrate that symmetric gait can be sub-optimal, at least in terms of energy economy, for individuals using a prosthesis on one leg.



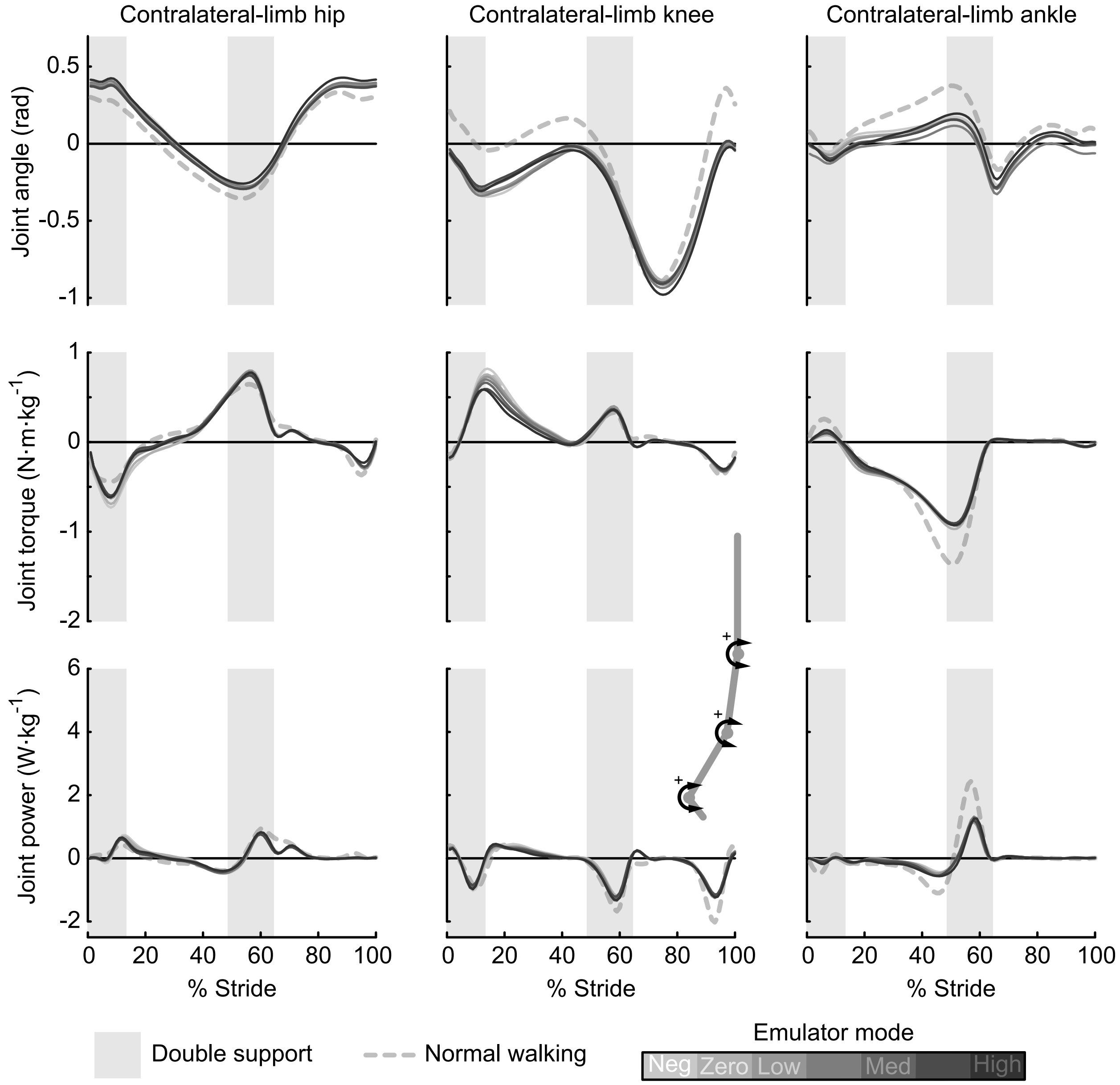
Supplementary Figure 1: Measured change in metabolic energy consumption compared to three candidate mechanical work correlates. Measured metabolic rate decreased with increasing ankle push-off. The change in metabolic rate was less than would be expected if Prosthesis work exactly replaced muscle work. The change in metabolic rate was greater than would be expected if Center of Mass work were equivalent to muscle work. The change in metabolic rate was as would be expected if Joint work were equivalent to muscle work. Error bars indicate inter-subject standard deviation and *s indicate statistical significance.



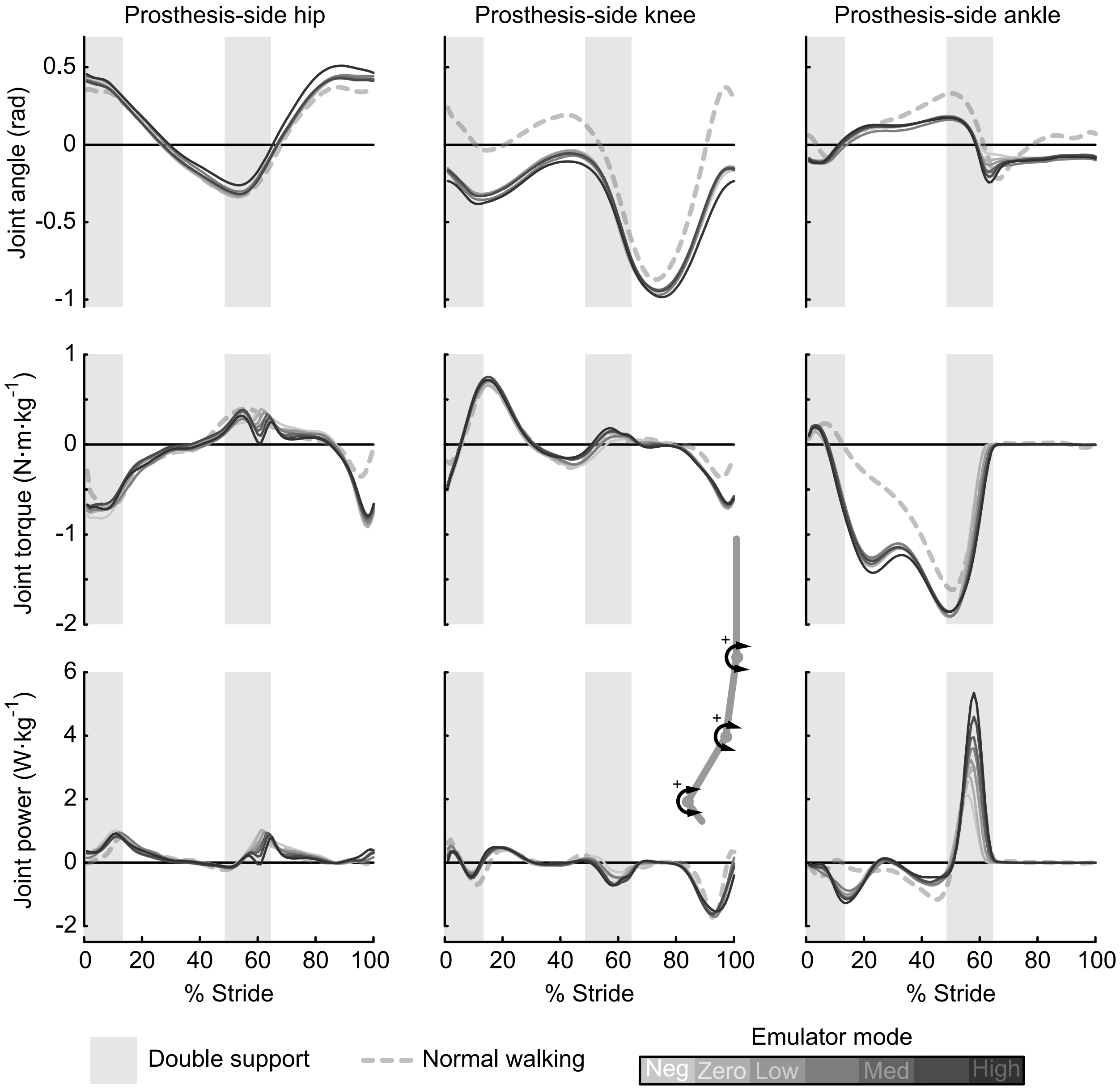
Supplementary Figure 2: Metabolic rate versus net prosthesis push-off work rate for individual subjects. Net metabolic rate (not change metabolic rate) is presented to illustrate inter-subject variability. Dashed lines indicate the predicted decrease in energy consumption if prosthesis work were to exactly replace positive muscle work. All data correspond to the same vertical axis, while horizontal location is self-consistent for each subject and corresponds to the scale provided.



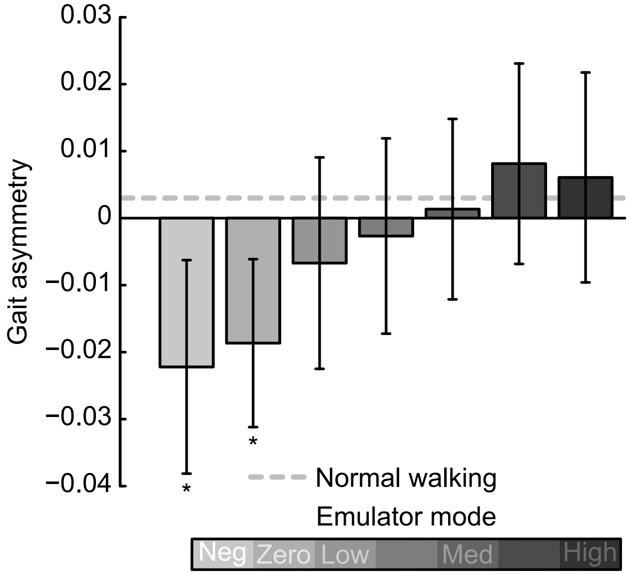
Supplementary Figure 3: Intact-limb adduction knee torque torque decreased with increasing prosthetic ankle push-off work. **A** Joint torque versus percent stride. Lines indicate average trajectories for each condition, with darker lines corresponding to conditions with higher prosthesis push-off work. **B** Peak torque during the collision phase. The apparent mismatch between peak values in these panels is a result of stride averaging to create the trajectories at left; peak values at right were calculated on each individual step and then averaged. Error bars indicate inter-subject standard deviation and *s indicate statistical significance.



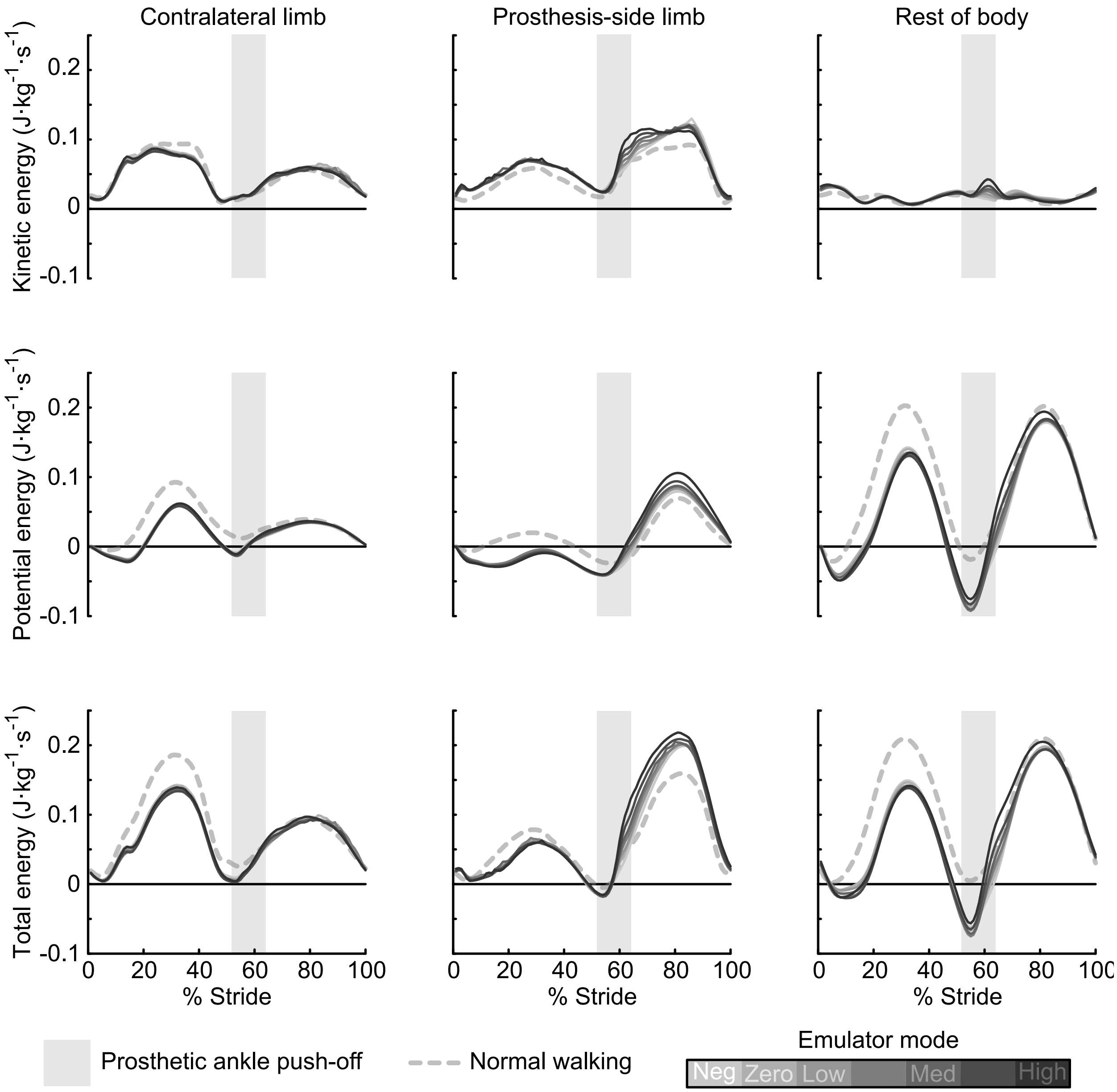
Supplementary Figure 4: Joint angle, torque, and power for the ankle, knee, and hip joints on the intact-side leg. Lines indicate average trajectories for each condition, with darker lines corresponding to conditions with higher prosthesis push-off work. Shaded region roughly indicates the double support period.



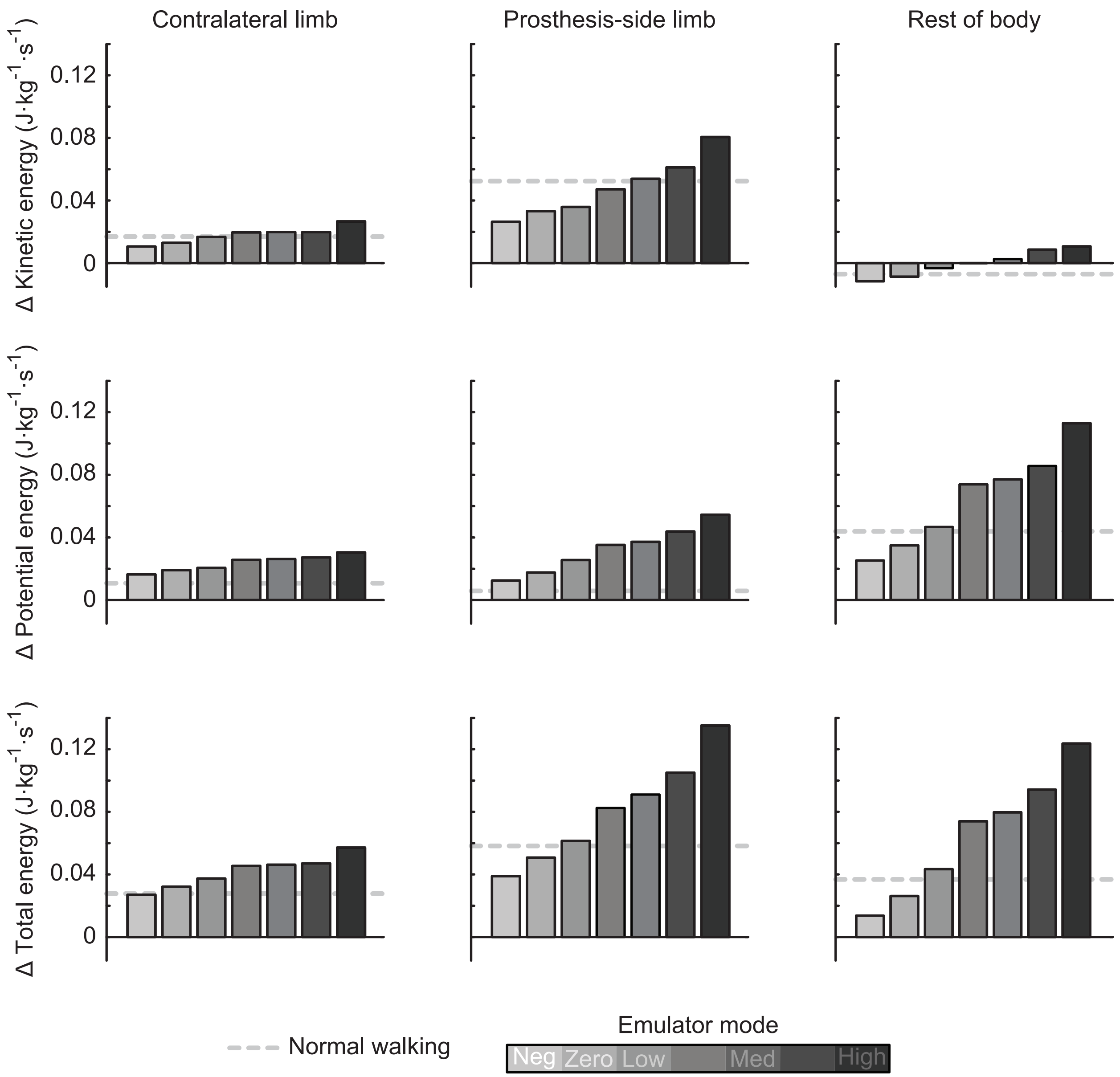
Supplementary Figure 5: Joint angle, torque, and power for the ankle, knee, and hip joints on the prosthesis-side leg. Lines indicate average trajectories for each condition, with darker lines corresponding to conditions with higher prosthesis push-off work. Shaded region roughly indicates the double support period.



Supplementary Figure 6: Gait asymmetry was affected by prosthetic ankle push-off work. Shading indicates different conditions. Error bars indicate inter-subject variability, *s indicate asymmetry is statistically significant compared to 0.



Supplementary Figure 7: Kinetic, potential, and total (the sum of kinetic and potential) energies of the whole prosthesis-side limb, contralateral limb, and the rest of the body, defined as everything other than the legs. 0% Stride corresponds to prosthesis-side heel strike. Lines indicate average trajectories for each condition, with darker lines corresponding to conditions with higher prosthesis push-off work. Shaded region roughly indicates the period of prosthetic ankle push-off.



Supplementary Figure 8: Change, across the period of prosthetic ankle push-off, in the kinetic, potential, and total (the sum of kinetic and potential) energies of the whole prosthesis-side limb, contralateral limb, and the rest of the body, defined as everything other than the legs. Shading indicates different conditions.