Muscle-tendon mechanics explain unexpected effects of exoskeleton assistance on metabolic rate during walking

Supplementary Materials

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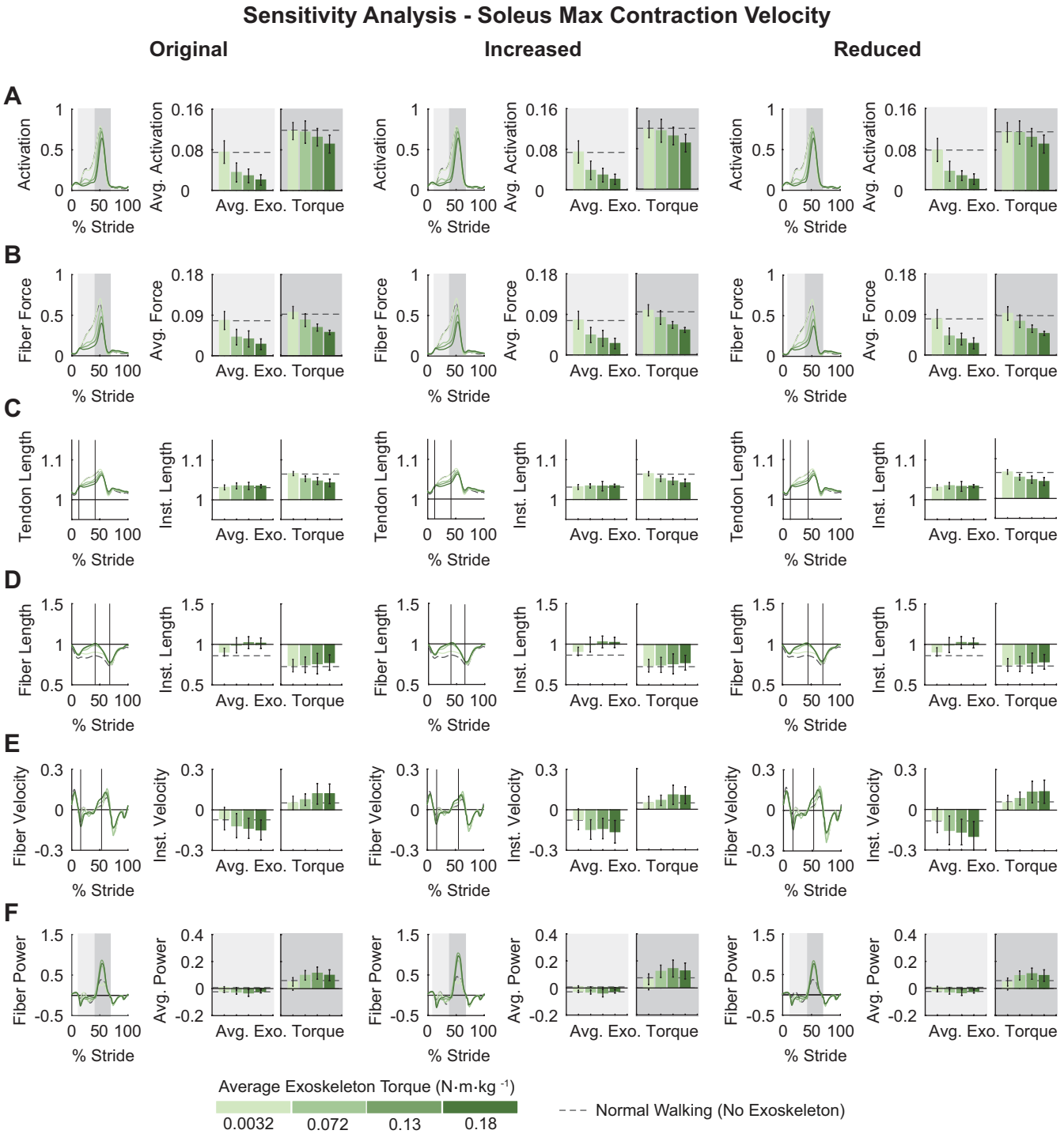

Figure S1. Sensitivity Analysis: Exoskeleton-side soleus muscle-tendon mechanics with varying soleus maximum fiber contraction velocities. Trends in muscle mechanics were insensitive to changes in maximum fiber contraction velocity. (A) Soleus activation. (B) Soleus muscle fiber force normalized to maximum isometric force. (C) Tendon length normalized to tendon slack length. (D) Soleus muscle fiber length normalized to optimal fiber length. (E) Soleus muscle fiber velocity normalized to maximum fiber shortening velocity. (F) Soleus muscle fiber power normalized to body weight. Left panel shows results with original maximum contraction velocity, middle panel shows results with 20% increased maximum contraction velocity, right panel shows results with 20% reduced maximum contraction velocity. Each curve is a subject-average ($N = 8$) trajectory. Bars and whiskers are subject means and standard deviations. Shaded bar plots represent subject-wise integration of corresponding trajectories over the shaded region. Unshaded bar plots represent subject-average instantaneous values of corresponding trajectories. Darker colors indicate higher values. Normal walking is shown by gray dashed lines.

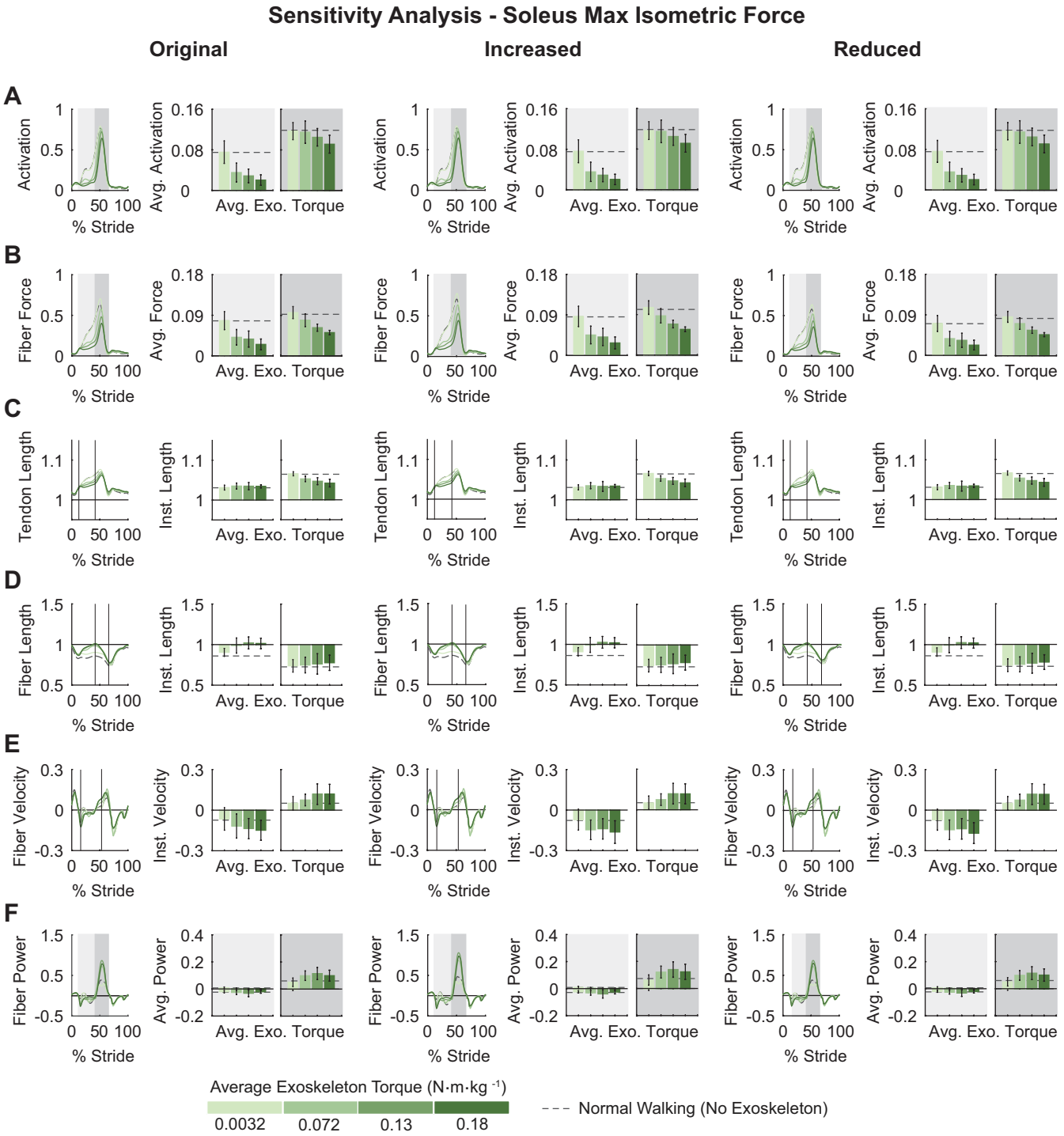

Figure S2. Sensitivity Analysis: Exoskeleton-side soleus muscle-tendon mechanics with varying soleus maximum isometric forces. Trends in muscle mechanics were insensitive to changes in maximum isometric force. (A) Soleus activation. (B) Soleus muscle fiber force normalized to maximum isometric force. (C) Tendon length normalized to tendon slack length. (D) Soleus muscle fiber length normalized to optimal fiber length. (E) Soleus muscle fiber velocity normalized to maximum fiber shortening velocity. (F) Soleus muscle fiber power normalized to body weight. Left panel shows results with original maximum isometric force, middle panel shows results with 10% increased maximum isometric force, right panel shows results with 10% reduced maximum isometric force. Each curve is a subject-average ($N = 8$) trajectory. Bars and whiskers are subject means and standard deviations. Shaded bar plots represent subject-wise integration of corresponding trajectories over the shaded region. Unshaded bar plots represent subject-average instantaneous values of corresponding trajectories. Darker colors indicate higher values. Normal walking is shown by gray dashed lines.

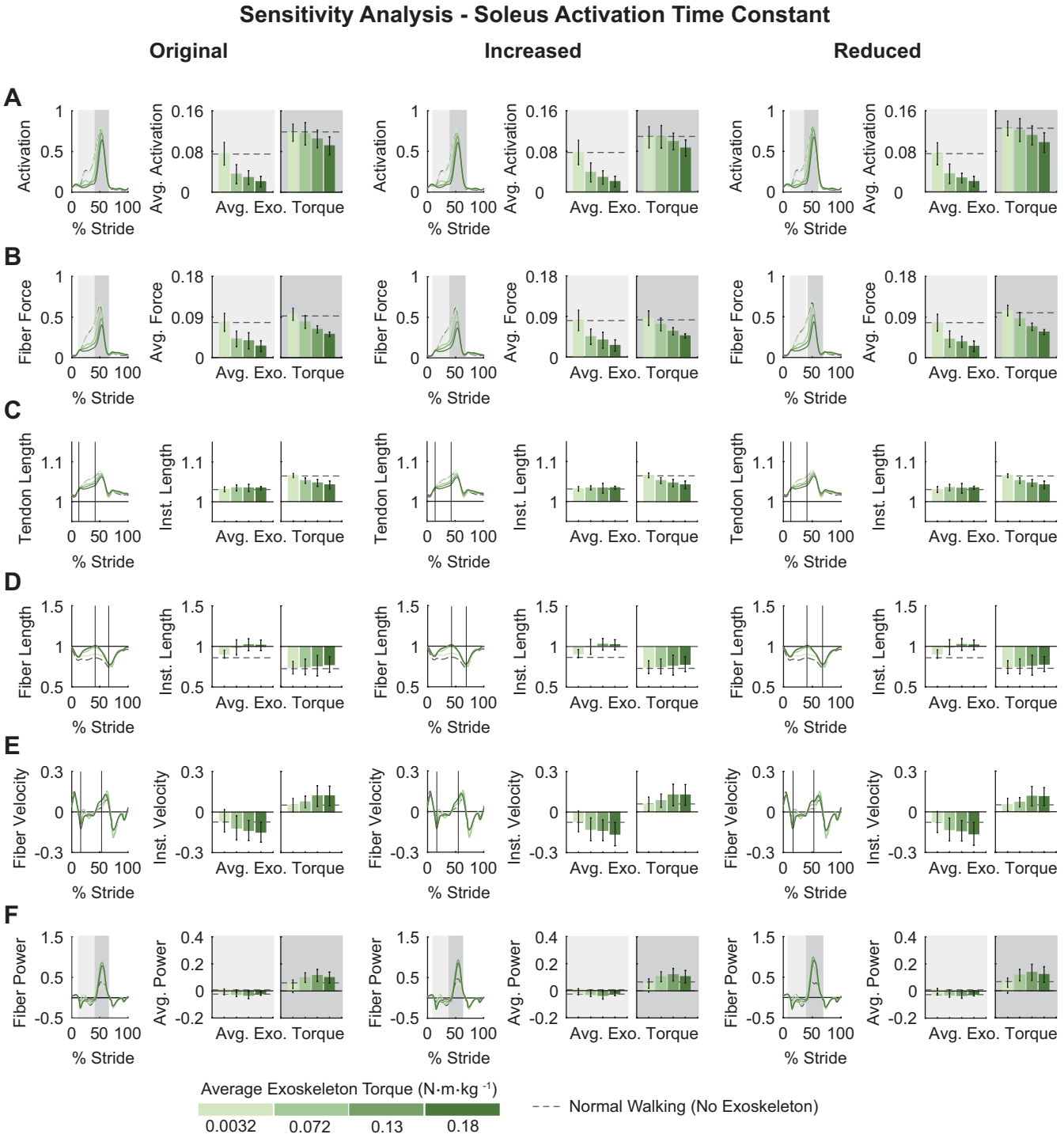

Figure S3. Sensitivity Analysis: Exoskeleton-side soleus muscle-tendon mechanics with varying soleus activation time constants. Trends in muscle mechanics were insensitive to changes in activation time constant. (A) Soleus activation. (B) Soleus muscle fiber force normalized to maximum isometric force. (C) Tendon length normalized to tendon slack length. (D) Soleus muscle fiber length normalized to optimal fiber length. (E) Soleus muscle fiber velocity normalized to maximum fiber shortening velocity. (F) Soleus muscle fiber power normalized to body weight. Left panel shows results with original activation time constant, middle panel shows results with 10% increased activation time constant, right panel shows results with 10% reduced activation time constant. Each curve is a subject-average ($N = 8$) trajectory. Bars and whiskers are subject means and standard deviations. Shaded bar plots represent subject-wise integration of corresponding trajectories over the shaded region. Unshaded bar plots represent subject-average instantaneous values of corresponding trajectories. Darker colors indicate higher values. Normal walking is shown by gray dashed lines.

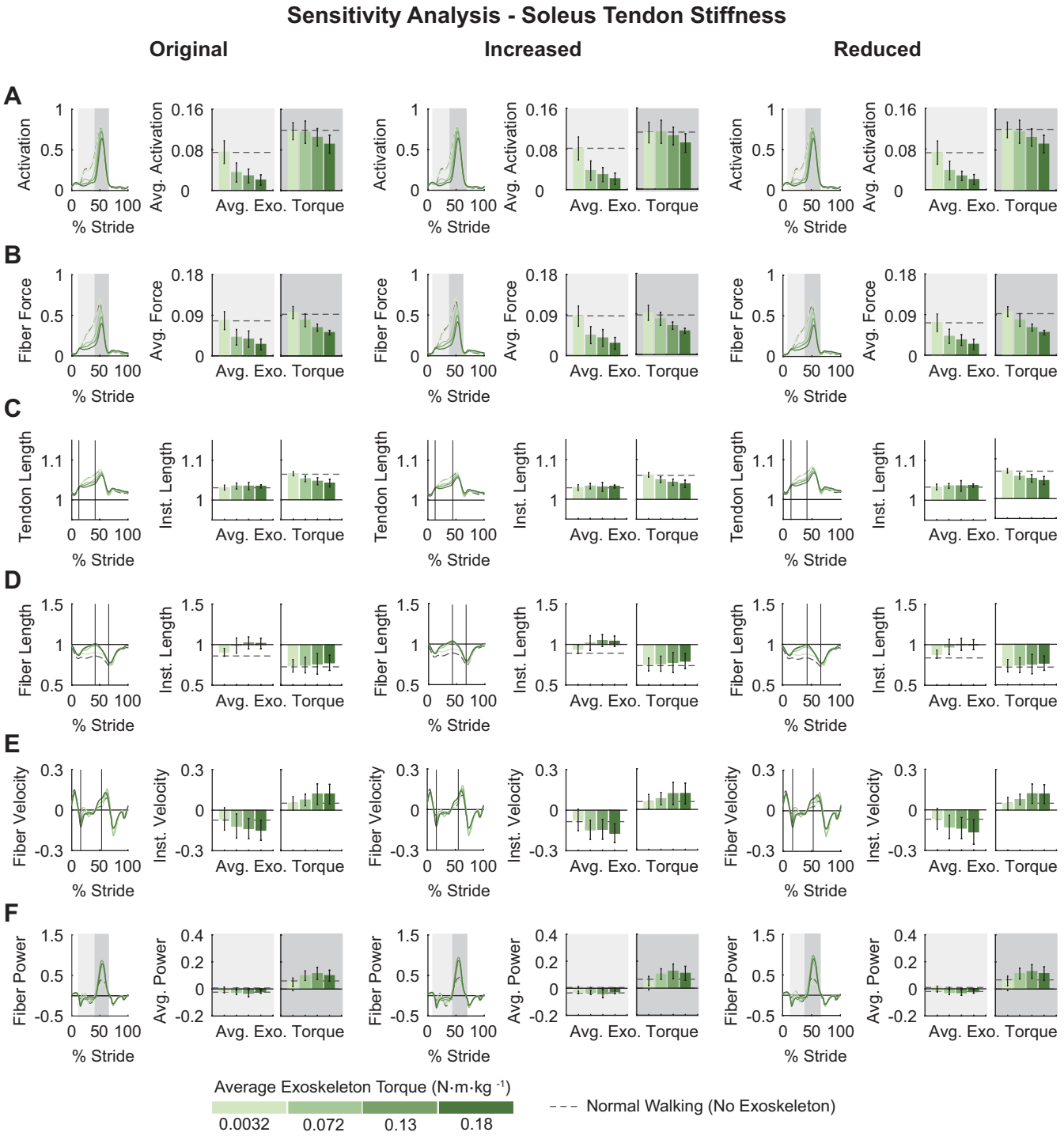

Figure S4. Sensitivity Analysis: Exoskeleton-side soleus muscle-tendon mechanics with varying soleus tendon stiffnesses. Trends in muscle mechanics were insensitive to changes in tendon stiffness. (A) Soleus activation. (B) Soleus muscle fiber force normalized to maximum isometric force. (C) Tendon length normalized to tendon slack length. (D) Soleus muscle fiber length normalized to optimal fiber length. (E) Soleus muscle fiber velocity normalized to maximum fiber shortening velocity. (F) Soleus muscle fiber power normalized to body weight. Left panel shows results with original tendon strain at maximum isometric force, middle panel shows results with 1% absolute reduction in tendon strain at maximum isometric force, right panel shows results with 1% absolute increase in tendon strain at maximum isometric force. Each curve is a subject-average ($N = 8$) trajectory. Bars and whiskers are subject means and standard deviations. Shaded bar plots represent subject-wise integration of corresponding trajectories over the shaded region. Unshaded bar plots represent subject-average instantaneous values of corresponding trajectories. Darker colors indicate higher values. Normal walking is shown by gray dashed lines.

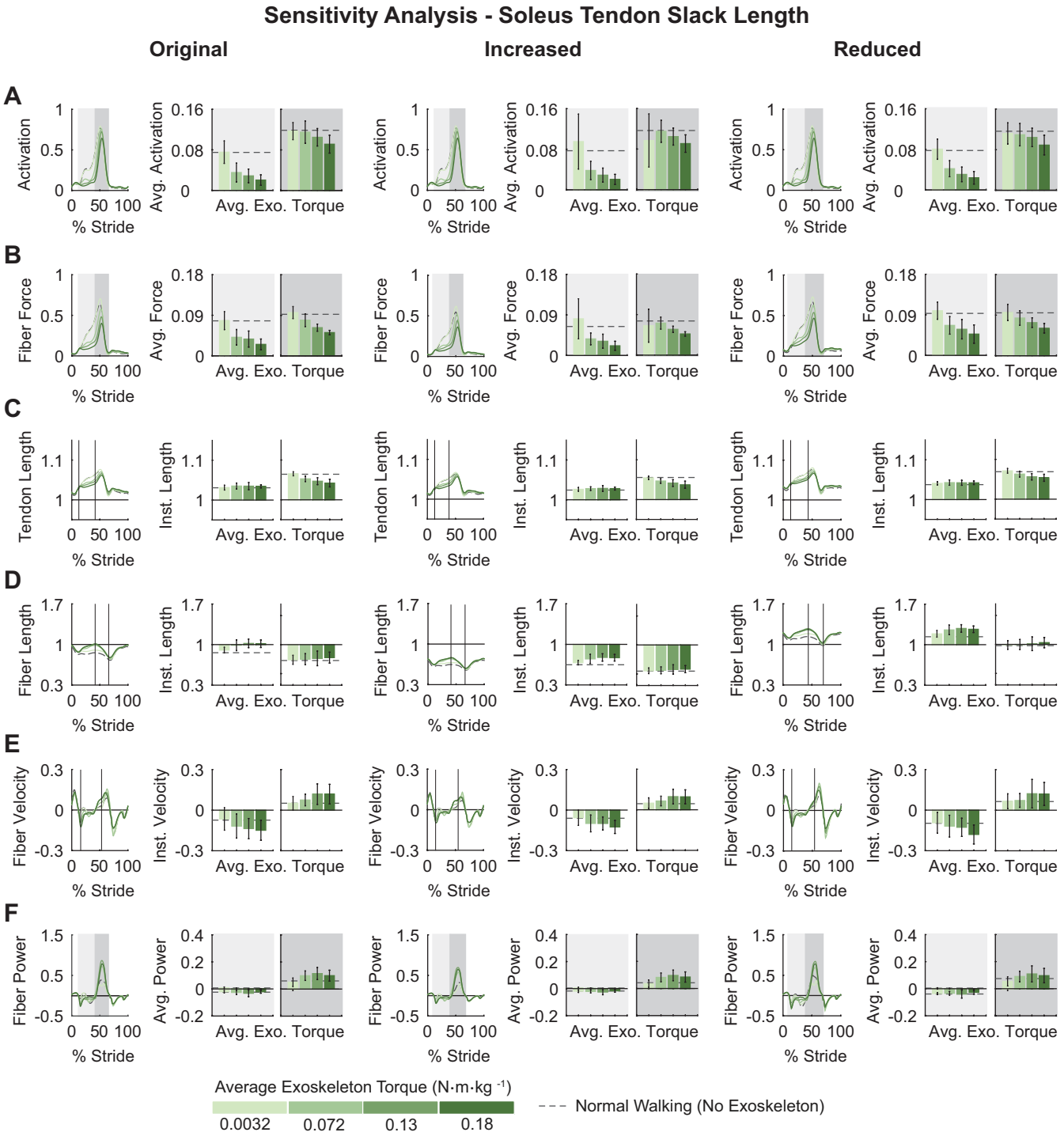

Figure S5. Sensitivity Analysis: Exoskeleton-side soleus muscle-tendon mechanics with varying soleus tendon slack lengths. Trends in muscle mechanics were insensitive to changes in tendon slack length. (A) Soleus activation. (B) Soleus muscle fiber force normalized to maximum isometric force. (C) Tendon length normalized to tendon slack length. (D) Soleus muscle fiber length normalized to optimal fiber length. (E) Soleus muscle fiber velocity normalized to maximum fiber shortening velocity. (F) Soleus muscle fiber power normalized to body weight. Left panel shows results with original tendon slack length, middle panel shows results with 5% increased slack length, right panel shows results with 5% reduced tendon slack length. Each curve is a subject-average ($N = 8$) trajectory. Bars and whiskers are subject means and standard deviations. Shaded bar plots represent subject-wise integration of corresponding trajectories over the shaded region. Unshaded bar plots represent subject-average instantaneous values of corresponding trajectories. Darker colors indicate higher values. Normal walking is shown by gray dashed lines.

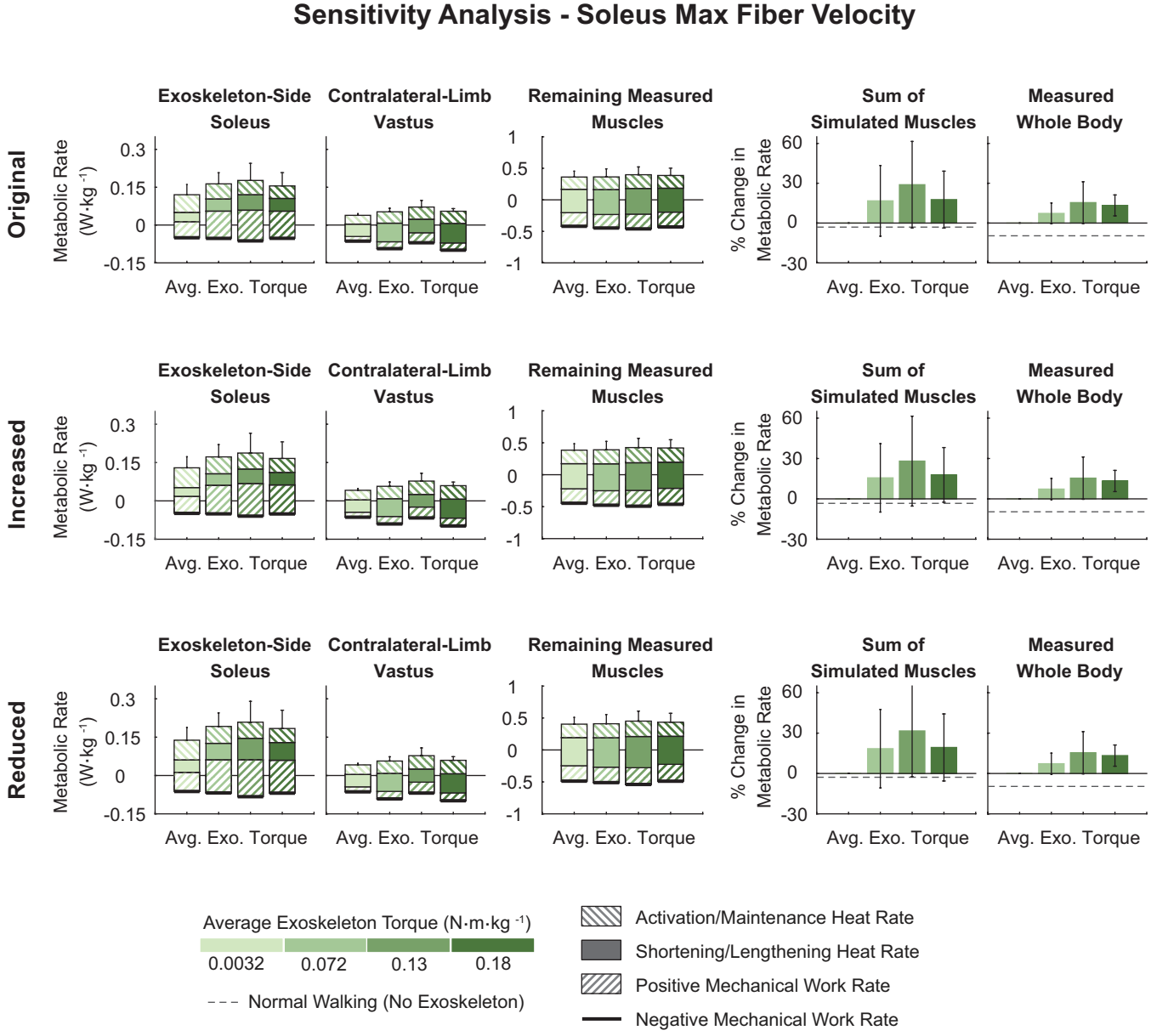

Figure S6. Sensitivity Analysis: Estimated individual muscle and sum of simulated muscles metabolic rate with varying soleus maximum fiber contraction velocities. Trends in muscle metabolic rate were insensitive to changes in maximum fiber contraction velocity. *From left to right:* Estimated exoskeleton-side soleus metabolic rate; estimated contralateral-limb vastus metabolic rate; estimated metabolic rate of the remaining muscles with electromyographic data; estimated percent change in the sum of the simulated muscle metabolic rates; and measured percent change in whole-body metabolic rate. The top rows show results with original tendon slack length, the middle row shows results with increased tendon slack length, and the bottom row shows results with reduced tendon slack length. Darker colors indicate higher values. Normal walking is shown by a gray dashed line. Bars and whiskers are subject means and standard deviations. Bar shadings represent different muscle heat and work rates. The solid black line at the base of each bar shows the average negative mechanical work rate. Data from $N = 8$ subjects except for plots of the contralateral-limb vastus metabolic energy consumption, for which $N = 5$.