Isolating the energetic consequences of mechanically imposed reductions in ankle and knee flexion during gait

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Introduction
Post-stroke gait is influenced by paretic limb weakness and marked by increases in metabolic cost. Weakness at the ankle is associated with reduced peak ankle power and propulsion, and knee extension is the cornerstone of “stiff-knee gait,” which results in compensatory mechanics including hip hiking and circumduction [1]. Post-stroke gait interventions often seek to improve paretic ankle and knee function thereby reducing the need for the compensations assumed to contribute to increased metabolic cost [2, 3]. However, the design of these interventions is limited since ankle and knee flexion are interrelated, making the independent roles of ankle and knee dysfunction on metabolic efficiency difficult to discern. Using a knee brace and custom 3D printed ankle stay, this study isolated the contributions of unilaterally reduced ankle flexion, knee flexion, and ankle+knee flexion on walking outcomes and energetics. Our hypotheses are: (h1) reduced ankle and knee flexion will result in decreased propulsion and increased circumduction, respectively, (h2a) Reduced ankle + knee flexion will yield the highest metabolic cost, and (h2b) limiting ankle flexion will be more metabolically expensive than limiting the knee.

Methods
Data were recorded for 15 (7M/8F) unimpaired controls walking (0.8ms⁻¹) for 7 mins in the following conditions: braced control (unlocked), unilaterally fixed ankle (uni-ank), unilaterally fixed knee (uni-kne), and unilaterally fixed ankle and knee (uni-a+k). We converted recorded rates of oxygen consumption and carbon dioxide production to metabolic powers [4]. A motion analysis system recorded 3D positions of markers placed on the pelvis and lower limbs. Simulations performed in OpenSim (v3.3) used a lower limb model adapted from a full-body model and scaled to participants [5]. Inverse kinematics, inverse dynamics, and analysis tools were used to compute joint angles, moments, and powers, respectively. Limb circumduction was calculated as maximum lateral foot displacement during swing [1]. Ground reaction forces measured on an instrumented dual-belt treadmill were used to identify peak propulsion. Outcome measures were averaged over 10 consecutive gait cycles, and statistical significance between conditions was determined by paired t-tests (p<0.05) with Bonferroni correction for multiple comparisons.

Results and Discussion
Peak propulsion on the locked limb (Fig 1a.) was significantly decreased in uni-ank and uni-a+k conditions compared to unlocked, demonstrating that restricting the ankle limited subjects’ capacity to propel forward. Additionally, hip circumduction (Fig 1b.) was significantly higher in uni-kne and uni-a+k conditions as compared to uni-ank condition, reinforcing the interaction between reduced knee flexion and circumduction. These results support h1 and demonstrate the effectiveness of mechanical bracing to elicit compensatory strategies characteristic of post-stroke gait. While metabolic cost (Fig 1c.) in the uni-a+k condition was significantly higher than unlocked and uni-kne, it was not significantly higher than the uni-ank condition, so we reject h2a. Additionally, the uni-ank condition was not significantly more metabolically expensive than uni-kne condition; therefore, we reject h2b. However, we note that both the uni-ank and uni-a+k conditions are significantly higher than the unlocked condition, indicating that regardless of restrictions in knee flexion, any direct restriction on the ankle is metabolically detrimental. Further, the significant increase in metabolic rate between uni-kne and uni-a+k suggests that combined restriction of the ankle and knee is more metabolically detrimental than restriction of the knee in isolation.

Significance
These results confirm that the combined impacts of reduced ankle and knee flexion are more detrimental metabolically than reduced knee flexion alone, providing support for the potential of ankle-based rehabilitative technologies in persons post-stroke to provide a metabolic benefit.

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References

Figure 1. Subject averaged (a) locked limb peak propulsion, (b) locked limb hip circumduction, and (c) net metabolic rate are shown with standard errors for unlocked, uni-ank, uni-kne, and uni-a+k conditions.