Increasing Walking Speed Increases Lower-limb Capabilities For Generating Propulsive Forces

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Introduction: The propulsive force, or the posterior component of the force produced by the lower-limb on the ground during the last 50% of the stance phase, governs walking speed. This force is diminished in post-stroke gait, inhibiting stroke survivors from becoming community walkers [1]. The feasible force space (FFS) is a geometrical representation of forces able to be produced, and it provides insights about the capability of the limb to produce a larger propulsive force and therefore to increase walking speed. When a patient's propulsive force is maximized (visually represented by its placement on the edge of the FFS), it is impossible to increase walking speed until physical therapies and/or gait rehabilitation occurs to expand the patient's FFS. We hypothesize that the peak magnitude of feasible propulsive forces is largest at the fastest walking speed.

Methods: We analyzed four able-bodied subjects walking over-ground at speeds characterized by extra slow, slow, free, and fast magnitudes [2] using 3D models with 92 muscles and 23 degrees of freedom. At each walking speed for each subject, we computed feasible endpoint force spaces, which we defined as forces $\vec{F}$ in the anterior, superior, and lateral directions, resulting from the product of the inverse kinematic Jacobian, $\vec{J}$, the muscle moment arms matrix, $\vec{R}$, and the maximum isometric muscle forces, $\vec{F_o}$: $\vec{F} = \vec{J}^{-T}\vec{R}\vec{F_o}$ [3]. The forces were scaled according to the mass of each subject. A 3D convex hull generated by the force vectors was produced and, due to the nature of the muscle contributions in the posterior direction, the 3D FFS was sliced along the sagittal plane to investigate the magnitude of the peak propulsive forces. To test our hypothesis concerning feasible forces increasing with speed, we compared the forces, $\vec{F}$, using a right-tailed t-test at $\alpha = 0.05$.

Results: The maximum feasible propulsive force was produced at the fastest walking speed (Figure 1). Slow speed maximum feasible propulsive forces are greater than the extra slow feasible forces ($p < 0.01$), free speed feasible forces are greater than the slow and extra slow feasible forces ($p < 0.01$), and fast speed feasible forces are greater than the free, slow, and extra slow feasible forces ($p < 0.01$). These feasible force trends match well with experimental trends. Importantly, there are significant reserves available to produce larger propulsive forces.

Conclusions: Slower walking speeds limit the lower limb capacity, generating smaller feasible propulsive forces during unimpaired gait. Future work will analyze feasible propulsive forces during hemiparetic post-stroke gait. It will consider physiology–informed muscle forces. The FFS of able-bodied walkers allows for a better understanding of treatment and rehabilitation efforts to improve propulsive force and walking speed for impaired walkers.

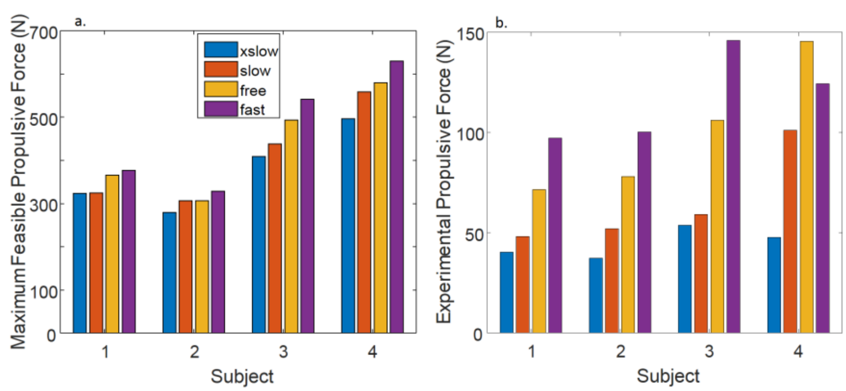

Figure 1: Maximum feasible propulsive force analysis for four able-bodied walkers. Future work will analyze additional able-bodied walkers. a.) Maximum feasible propulsive forces at different walking speeds for each subject; b.) Corresponding experimental propulsive forces for each subject.

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References: [1]: Hsiao, H., et al., *Mechanisms used to increase peak propulsive force following 12-weeks of gait training in individuals poststroke.* J Biomech, 2016. **49**(3): p. 388-95. [2]: Liu, M.Q., Anderson, F.C., Schwartz, M.H. and Delp, S.L., *Muscle contributions to support and progression over a range of walking speeds.* Journal of Biomechanics, Nov 2008, 41(15):3243-3252. (2008). [3]: Valero-Cuevas FJ. Fundamentals of Neuromechanics, 2016.