Estimation of Human Ankle Impedance During Late Stance Phase of Walking

Background: Human *joint mechanical impedance* is fundamental to our ability to interact with the environment, describing the stiffness and damping properties of the joint. The nervous system regulates joint impedance to adapt to unexpected changes in task dynamics, for instance walking over uneven terrain [1]. However, current knowledge of joint impedance modulation is hindered by difficulties measuring joint torque response to perturbations during functional tasks, such as walking. It is critical to characterize ankle impedance during walking to elucidate how these properties are naturally regulated in human locomotion, and provide a foundation for the development of biomimetic assistive devices and their control systems. Methods have recently been developed to overcome some of the associated challenges; Rouse *et al.* accurately estimated ankle impedance during walking throughout early-mid stance phase [1], while Lee *et al.* have characterized ankle impedance from pre-swing phase to early loading response using a wearable ankle robot [2]. Impedance in late stance phase, not studied previously, is particularly important to characterize since the majority of mechanical power responsible for forward propulsion during gait is produced at this time [3]. However, motion and deformation of foot segments following heel rise pose challenges to torque measurement during late stance; thus, previous work has focused on other regions of the gait cycle. Motion capture studies have analyzed how the fore-foot, mid-foot, and rear-foot segments move relative to each other, the shank, and the ground [4]; but these data have not previously been used in conjunction with identification of joint impedance. This work quantifies ankle impedance during this crucial portion of stance phase, providing insight into how active power generation in locomotion affects joint mechanics.

Methods: This preliminary study was comprised of 6 healthy, abled bodied subjects (3 male, 3 female, age 24 ± 3 years, weight 73 ± 11 kg), with no history of neurological impairment. A single degree of freedom mechatronic platform was used to apply perturbations to the ankle and measure relevant force data at two distinct timing points in late stance phase, during the push off region of the gait cycle. Perturbations occurred in both the plantarflexion and dorsiflexion direction. A second-order parametric model comprised of stiffness, damping and inertia components relates the perturbation-induced changes in ankle angle to the resulting joint torque response. Least-squares system identification was used to determine impedance. Using data from aforementioned motion capture studies, a novel time varying, subject specific transformation was developed to resolve the ground reaction force to the ankle, allowing for accurate and robust torque measurements during mid-foot deformation.

Results / Discussion: The second-order model comprised of stiffness, damping, and inertia accurately characterized ankle mechanics during late stance phase (VAF = 90 ± 7.7%.). The stiffness component of impedance decreased linearly throughout late stance from values reported pre-heel rise to the relatively low stiffness found during swing phase [5]. When averaged across subjects, time points and perturbation direction, the mean inter-subject variation in stiffness was found to be 0.58 ± 0.2 Nm/rad/kg. Mean damping estimates during late stance were found to be relatively constant, though exhibited large standard error indicating inconsistencies across subjects. A mean inter-subject variation of 0.009 ± 0.0008 Nms/rad/kg was found for damping estimates when averaged across subjects, time point, and perturbation direction. Damping estimates increased during late stance when compared to damping values found in early and mid-stance. These findings are in agreement with previously reported work showing increased damping in preparation for toe-off [5]. Mean inertia estimates matched previously reported values during gait [5], and were consistent across perturbation time point and direction in late stance, though exhibited high standard error (0.007 ± 0.004 kgm^2). High variation can be attributed to foot instabilities causing a multi-joint reaction to perturbation during heel rise as a result of the smaller base of support (BoS) and large separation between center of mass and BoS [6]. Due to the small sample size, statistical inferences cannot yet be gleaned; future work will collect additional data.

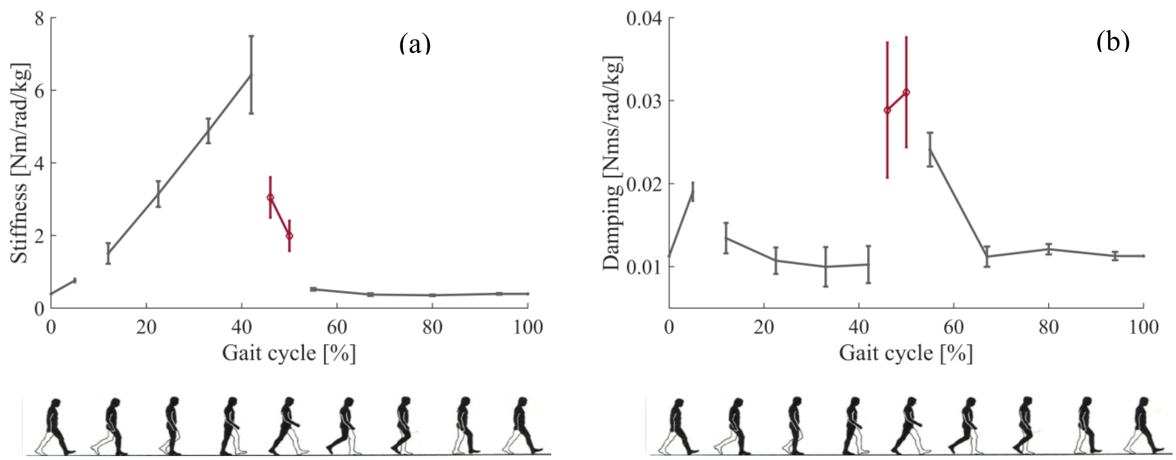

Fig. 1. Time varying ankle impedance during walking. Body weight normalized ankle stiffness (a) and damping (b) are reported for eleven time points characterizing the complete gait cycle. Grey traces denote results from previous studies analyzing ankle impedance from pre-swing to mid stance [5]. Red traces indicate average stiffness and damping results across perturbation direction during late stance.

References:

[1] E. J. Rouse, L. J. Hargrove, E. J. Perreault, and T. A. Kuiken, "Estimation of Human Ankle Impedance During the Stance Phase of Walking," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 22, no. 4, pp. 870-878, 2014.

[2] H. Lee and N. Hogan, "Investigation of human ankle mechanical impedance during locomotion using a wearable ankle robot," in *2013 IEEE International Conference on Robotics and Automation*, 2013, pp. 2651-2656.

[3] D. A. Winter, "Biomechanics of human movement with applications to the study of human locomotion," (in eng), *Critical reviews in biomedical engineering,* vol. 9, no. 4, pp. 287-314, 1984 1984.

[4] A. Leardini, M. G. Benedetti, L. Berti, D. Bettinelli, R. Nativo, and S. Giannini, "Rear-foot, mid-foot and fore-foot motion during the stance phase of gait," *Gait & Posture,* vol. 25, no. 3, pp. 453-462, 3// 2007.

[5] H. Lee, E. J. Rouse, and H. I. Krebs, "Summary of human ankle mechanical impedance during walking," *IEEE journal of translational engineering in health and medicine,* vol. 4, pp. 1-7, 2016.

[6] V. Lugade, V. Lin, and L. S. Chou, "Center of mass and base of support interaction during gait," *Gait Posture,* vol. 33, no. 3, pp. 406-11, Mar 2011.