

Gait strategy changes with walking speed to accommodate biomechanical constraints

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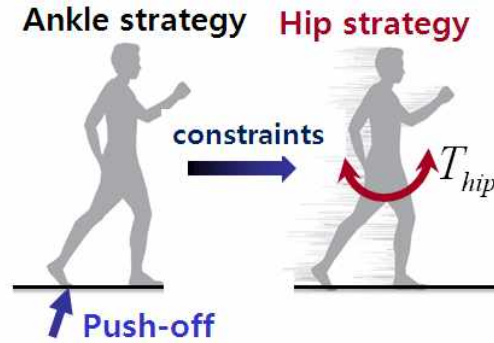
INTRODUCTION

Steady state human locomotion at level ground needs compensatory energy input against impulsive energy loss during heel strike. Ground push-off by the stance leg right before the onset of double support phase appeared to be four times energy efficient than the an active hip torque generation during the swing phase [1]. However, if there is biomechanical constraint applied to the maximum allowable ankle push-off, despite its cost effectiveness, the nervous system may need to employ active hip torque to compensate heel strike energy loss to maintain steady state walking, as similar to the postural strategy changes from ankle to hip strategy to accommodate biomechanical constraints in response to backward perturbation [2]. In this study, we hypothesized that the gait strategy changes from ankle strategy (that compensates heel strike energy loss mostly by the ankle joint push-off impulse) to hip strategy (that generates additional energy input using active hip joint torque during the swing phase) to accommodate biomechanical constraints at ankle joint torque.

METHODS

Eight healthy male volunteers aged 23-27 participated in this study after signing informed consent approved by KAIST IRB. Subjects walked along the 10m walkway with randomly ordered five different gait frequencies given by the auditory cues while having almost constant step lengths. The uniform interval of gait frequencies was obtained by the one third of gait frequency difference between the self-selective and maximum gait frequency. To examine whether the required increase in push-off impulse can be controlled by the nervous system, subjects also performed added inertia trials with weighted backpack of 15~20% of their body mass. Ground reaction forces of each foot and joint kinematics were measured by dual force plates and optical motion capture system, respectively.

A.



B.

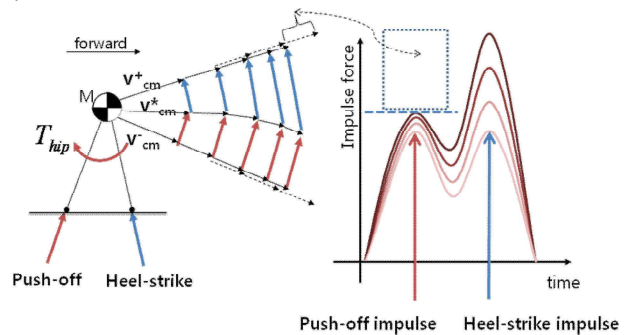


Figure 1: (A) Hypothesis of gait strategy change to accommodate biomechanical constraints of the ankle. (B) Push-off impulsive force is saturated while heel strike impulsive force is still increasing with walking speed.

Both push-off and heel strike impulses are calculated by integrating impulsive ground reaction forces measured from the force platform over the duration of impulsive forces. Several methods are considered to define the duration of impulsive force – COM velocity hodograph, COM work (power), and vertical ground reaction forces [3]. COM hodograph shows vertical and forward component of COM velocity, and the points where the maximum angular excursion of COM velocity occurs are defined as upper or lower limits of the duration. Work done by push-off impulse shows positive power during the step-to-step transition (double support) phase, while work done by heel strike collision shows negative power. The time

duration of overlapped positive and negative power is used to define the duration of impulse. We chose another method which uses vertical ground reaction forces. The peak values of the push-off and heel strike impulsive forces are defined as start and end point of each impulsive force, respectively.

Mechanical energy was calculated by the sum of potential and the kinetic energy of the center of mass using a sacral marker.

RESULTS AND DISCUSSION

Peak impulsive force of both push-off and heel strike were not significantly different in magnitudes at slow step frequency, but push-off impulsive forces appeared to saturate for the higher step frequency trials. The magnitudes of the impulse were almost similar with each other at slower gait speed while the push off impulse was significantly smaller than the heel strike impulse at higher step frequency due to the saturated push off impulsive forces. The differences in the mechanical energy between the beginning and the end of the swing phase were negligible at slower step frequency, while they monotonically increased with step frequency. With added inertia, the constraint on ankle plantar flexion becomes active at slower gait speed than the control trials.

Biomechanical constraints on ankle joint torque was demonstrated by the saturated ankle joint push-offs. Increased mechanical energy during the swing phase implies that the nervous system employs active hip torque to compensate heel strike energy loss to maintain steady state walking despite its higher energy cost than the ankle push-offs. As was observed in the postural strategy change [2], the results suggest that biomechanical constraints induce gait strategy change from ankle to hip strategy.

CONCLUSIONS

Biomechanical constraints on ankle joint torque was demonstrated by the saturated ankle joint push-offs. Observed limitation on push-off propulsion force at higher gait speed would attribute to intrinsic muscle properties [4], while the heel strike impulsive force, which does not involve active muscle shortening but mostly involves passive muscle components, showed monotonic increase. Deficiency of push-off

impulsive pre-compensation against collision loss at high gait speed is complemented by hip torque actuation during the swing phase. Increased mechanical energy during the swing phase implies that the nervous system employs active hip torque to compensate heel strike energy loss to maintain steady state walking despite its higher energy cost

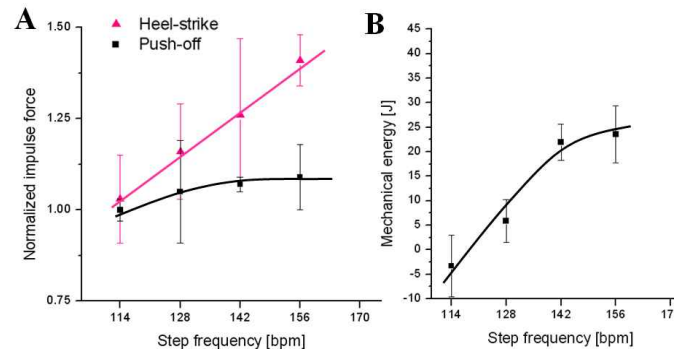


Figure 2: (A) Impulsive force of the ankle push-off and heel strike at double support phase. (B) Increase of mechanical energy during swing phase.

than the ankle push-offs. We also suggest that biomechanical constraints induce gait strategy change from ankle to hip strategy, as was observed in the postural strategy change [2].

Appropriate collision compensation by the combination of push-off propulsion and hip torque actuation would serve as an assessment of gait performance. We expect that the elderly who could not maintain steady state gait in response to the perturbation that requires gait strategy change, such as the increased inertia, walking on an inclined surface, and/or faster gait speed, may show inappropriate complementary hip torque engagement though their plantar flexor is significantly limited.

ACKNOWLEDGEMENTS

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