Is push-off propulsion the winning strategy for energy efficient gait acceleration?

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1 Introduction

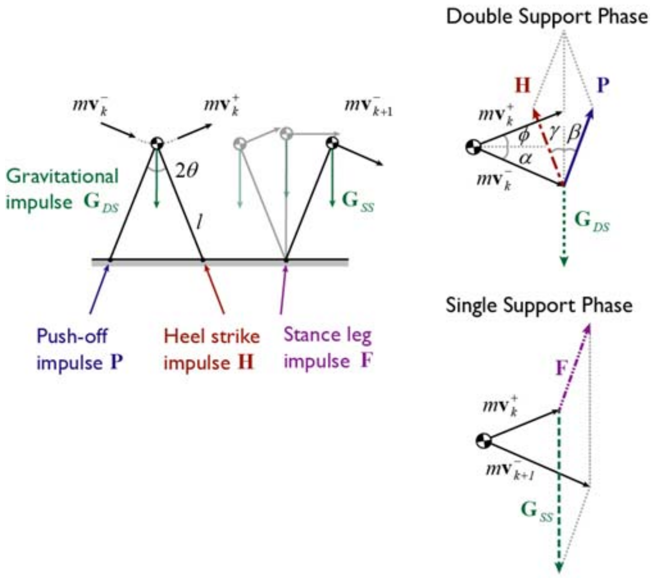
Experimental data showed that the compensatory push-off work during the double support phase almost matched with the collision loss, thereby almost negligible additional work was done to propel the CoM during the single support phase [1, 2] A simple biomechanical analysis showed that the observed energy balance during the double support phase appeared to be the energetically least costly gait [1-3]. Whereas the most of the previous experimental data were obtained from steady gait trials, most of our daily locomotion involves transient gait response such as gait acceleration, and/or deceleration. Therefore in this study, we examined whether the push-off propulsion during the double support phase would serve as a major energy source for gait acceleration. We also performed a simple biomechanical analysis to examine energetic optimality of accelerated gait.

2 Methods

To examine the energetic optimality of the gait acceleration, we calculated the theoretical optimal push-off impulse and the predicted values were compared to experimental data to validate the model prediction.

Seven healthy, young subjects participated in the over the ground walking experiments. Subjects accelerated their gait from zero to their maximum gait speed using self-selected acceleration. As control trials, we collected self-selected steady gait trial as well. Ground reaction force (GRF) of three consecutive steps and the corresponding leg configuration were measured by force platforms and an optical marker system, respectively. The mechanical works performed by the GRF during each single and double support phase were calculated to quantify gait acceleration strategy. The theoretical optimal push-off was predicted from the gravitational impulse model [2, 6]. Specific details are as follows.

The momentum of the center of mass (CoM) is changed by gravitational impulse (G), push-off (P) and heel strike (H) impulses and from the vector diagram of the momentum-impulse relationship (Fig. 1), we obtained the work done by the GRF for gait acceleration as follows:



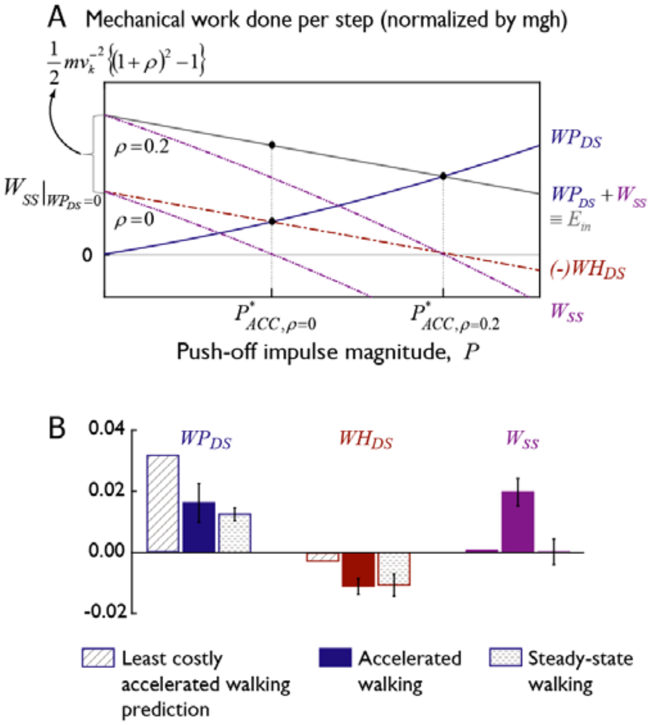
[Figure 1] Impulse-momentum diagram of the body's center of mass during double support and single support phase for the gait acceleration. α, ϕ, β, and γ are the directions of the pre- and post-collision velocities of the CoM and the push-off and heel strike impulses, respectively [6].

$$\begin{cases} WP_{DS} = \dfrac{P}{2m}\sin^2 2\theta \cdot \left(P + \dfrac{mv_k^-}{\tan 2\theta} - \dfrac{G_{DS}}{2\cos\theta}\right) \\ WH_{DS} = -\dfrac{1}{2}\cdot v_k^- \sin 2\theta \times \left\{mv_k^- \sin 2\theta - P\cos 2\theta + G_{DS}\cos\theta\right\} \\ W_{SS} = -(WP_{DS} + WH_{DS}) + \dfrac{1}{2}\cdot mv_k^{-2}\rho(\rho+2) \\ \quad = \dfrac{-\sin^2 2\theta}{2m}\left\{P - \left(mv_k^- \tan\theta + \dfrac{G_{DS}}{2\cos\theta}\right)\right\} \\ \quad \times\left(P + \dfrac{mv_k^-}{\tan\theta}\right) + \dfrac{1}{2}\cdot mv_k^{-2}\rho(\rho+2) \end{cases}$$

where $\mathbf{v}_k^-$ and $\mathbf{v}_k^+$ are the pre- and post-collision velocities of the CoM during the double support phase of k^{th} step, $\mathbf{v}_{k+1}^-$ is the pre-collision velocity of k+1 step's double support phase. P and G_{DS} are push-off and gravitational impulse during double support pahse, respectively, and WP_{DS}, WH_{DS}, and W_{SS} are work done by push-off, heel strike impulse, and stance leg respectively during the subscribed phase. The m is a body mass and for simplicity, we assumed the same momentum-impulse directions $(\alpha=\phi=\beta=\gamma=\theta)$. The acceleration ratio ρ is defined as the ratio of the increase in the pre-collision CoM speed per step. Then the optimal push-off P^* that minimizes the total energy input for gait acceleration is obtained as follows:

$$P^* = \arg\min_{P^*} |WP_{DS} + W_{SS}| = \arg\min_{P^*} \left(|WH_{DS}| - \frac{1}{2} \cdot m v_k^{-2} \rho(\rho+2) \right),$$
$$\textit{subject to } W_{SS} \geq 0$$

By imposing the constraint of positive work done during the single support phase, i.e., $W_{SS} \geq 0$ [1], the theoretically optimal push-off impulse is obtained as a quadratic form of the acceleration ratio ρ (Fig. 2A).



[Figure 2] (A) Model predictions of the energy cost of an accelerated walking. (B) The experimental data of mechanical work done per step by each impulse [6].

3 Results

The model prediction of optimal gait acceleration showed that the dominant energy input was supplied by push-off during the double support phase followed by zero net work done during single support phase as similar to those of steady gait trials (Fig. 2B). The model also predicts that the increase of push-off proportional to the acceleration for least costly gait acceleration. However, contrast to the model prediction of the increase of gait speed during the double support phase, the data showed significant energy increase during the single support phase while having energy balance between the push-off and heel strike during double support phase (Fig. 2B). The observed change of gait strategy was consistently reported in the previous studies of altering walking speed and uphill/downhill walking trials [4, 5].

4 Conclusions

In this study, we examined whether the push-off propulsion during the double support phase would serve as a major energy source for gait acceleration. As opposed to the model prediction of the increase of push-off proportional to the gait acceleration, the observed push-off did not changed much whereas the work done by the GRF during the single support phase was significantly increased. Considering that the push-off force is generated mostly by the plantar flexors, the consistent push-off forces may be attributed to the intrinsic muscle properties, such as limited increase in muscle contraction force at fast movement. Therefore, we suggest that the strategy of gait acceleration during single support phase worked as the subjects accommodated the physiological limitation on the magnitude of push-off propulsion [6].

5 Open Questions

Whether the change of gait strategy observed for other transient walking such as walk to run transition or uphill/downhill walking would be explained by the biomechanical constraints incorporating with movement economy could be the question to examine in the further study.

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