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The Powered Simplest Walking Model Explains the Different Vertical Ground Reaction Force Amplitudes at Elevated Walking Speeds

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Abstract:

The vertical component of walking ground reaction force (GRF) has attracted much attention in analyzing human gait. Its typical trajectory shows two peaks at the beginning and end of the stance phase. The first peak signifies step load acceptance, while the second peak is to accelerate the center of mass (COM) for the next step. As walking speed increases, these peaks grow at different rates, with the first peak's amplitude becoming larger. No mechanistic explanation has been provided for this change. Here, we used a simple walking model and the COM work rate trajectory to investigate the vertical GRF profile change. A step is usually energized by positive work (push-off) at its start, followed by energy dissipation. It is suggested that push-off is exerted by the ankle joint. At elevated walking speeds, the ankle's biomechanical power generation capacity may not be sufficient to energize the entire gait. Since push-off also limits the magnitude of step energy dissipation (collision), any shortfall in push-off is followed by increased collision, reflected in the first peak's rise in vertical GRF. This is supported by the observation that collision work exceeds push-off beyond a certain walking speed threshold (even walking $v = 1.35\ \mathrm{m} \cdot \mathrm{s}^{-1}$). Therefore, we also expect to observe different vertical GRF peak amplitudes when terrain challenges limit or disrupt the ankle's mechanical energy output. The vertical GRF unequal peaks may indicate that lower limbs are subjected to higher dissipations that might overstress them, and the required compensation is provided by over actuating of the other joint that might yield to their faster deterioration.

Introduction:

Walking is performed by exerting forces on the terrain. The reaction of the induced forces (Ground Reaction Forces: GRF) accelerates the walkers' Center of Mass (COM) in the direction of progression (Muller 2018). The vertical direction component is the largest since the legs support the weight (Masani, Kouzaki, and Fukunaga 2002). Thus, its analysis has attracted much attention. The vertical GRF profiles are affected by several factors, such as terrain complexity (Aminiaghdam and Rode 2017), state of vision (Majlesi, Farahpour, and Robertson 2020), age (Laufer 2005), etc. However, no mechanical explanation has been provided when the vertical GRF peaks' amplitudes are different.

It is suggested that the first peak of the vertical ground reaction force is due to weight acceptance (collision), and the second is due to ankle-generated force to accelerate the COM forward (Muller 2018). The walking factors may affect the magnitude of vertical GRF peaks. One example is a load bearing that distorts the vertical GRF profile (Aminiaghdam and Rode 2017). Aminiaghdam et al. (Aminiaghdam and Rode 2017) have suggested that greater weight acceptance loads and loading rates or lower unloading rates alter the vertical GRF peaks. It is also proposed that walking with a crouching posture leads to higher vertical GRFs and loading rates during early stance and lower vertical GRFs during the pre-swing phase (Aminiaghdam et al. 2017). It is further suggested that modeling the human leg as a spring and a damper, the damper shifts the vertical GRF to the right by increasing forces after the heel strike and decreasing forces at toe-off, resulting in an early lift-off (Aminiaghdam et al. 2017).

Based on the provided short introduction, no study explains the vertical GRF peak amplitude differences with affecting factors backed by the experimental data. Therefore, this investigation examines how the vertical GRF may be altered when walking velocity increases.

Materials and Methods:

We collected the GRF signals for 60 seconds at 960 Hz and converted to force using the method described by Collins et al. (Collins et al. 2009). The trials' velocities ranged from 0.8 $\mathrm{m} \cdot \mathrm{s}^{-1}$ to 1.4 $\mathrm{m} \cdot \mathrm{s}^{-1}$, and We randomized the order of the walking velocities for each subject. The GRFs were filtered by a third-order zero-phase Butterworth filter (cut-off 10 Hz). The methods described by Donelan et al. (Donelan, Kram, and Kuo 2002a) and Kuo et al. (Arthur D. Kuo, Donelan, and Ruina 2005) were used to calculate the COM velocity, COM power trajectory, and stance phases' works.

Statistical analysis was conducted using linear regression (Linear Mixed Effects Models, Statsmodels 0.15.0), with the parameters under study (COM work components) serving as the dependent variables. Trials walking velocity was considered as the continuous independent variable. Regression gains and associated p-values were reported to depict the relationships and significance. Subsequently, the COM work components' statistical results were used to estimate the COM work components' trends and the associated impulses (Arthur D. Kuo 2002) for walking velocities ranging from 0.8 $\mathrm{m} \cdot \mathrm{s}^{-1}$ to 1.6 $\mathrm{m} \cdot \mathrm{s}^{-1}$.

We invited a group of healthy adults to participate in our experiment: (age: 27.69 ± 5.21, mass: 71.0 ± 6.16 kg, six females and four males). The procedure was approved by the university Conjoint Health Research Ethics Board, and subjects provided written informed consent before the experiments. The subjects were given a few short trials to become familiar with the experimental conditions.

Simulation:

Using the GRF to calculate the push-off and collision impulses is somewhat arbitrary since the start or end points that define the integration periods need to be clarified. For instance, Adamczyk et al. (Adamczyk and Kuo 2009) suggested calculating collision and push-off impulses for the duration of the double support phase. It implies that all push-off works are induced by delay (Darici, Temeltas, and Kuo 2018), whereas it is proposed that push-off starts before the double support (Arthur D. Kuo, Donelan, and Ruina 2005). To overcome this problem, since COM power trajectories depict four distinct phases during the stance phase (Arthur D. Kuo, Donelan, and Ruina 2005), the collision and push-off works were calculated by time integration of each power phase. Accordingly, the push-off and collision impulses were calculated (Arthur D. Kuo 2002). The optimum push-off impulse and work were calculated by $po_{opt} = v_{ave} \cdot \tan\alpha$ and $PO_{opt} = 0.5po_{opt}^2$ for a given walking velocity, (Darici, Temeltas, and Kuo 2018; A. D. Kuo 2001). Having suboptimal push-off (po_{rand}) as a fraction of optimum push-off, its work was also calculated as $PO_{rand} = 0.5po_{rand}^2$, and the associated collision impulse and its work were computed as $co_{rand} = v_{ave}\sin 2\alpha - po_{rand}\cos 2\alpha$ and $CO = 0.5co_{rand}^2$, respectively (Arthur D. Kuo 2002). The post-transition compensation was defined as the difference between the suboptimal collision work and push-off.

Results:

The average vertical GRF and COM power trajectories demonstrated changes with walking velocity. It appeared that vertical GRF and COM power peaks and their relative timing altered (Figure 1). The statistical analysis showed that the push-off and collision works significantly changed with the walking velocity (Table 1). The calculated gains were used to develop

experimental push-off and collision works trajectories and their associated impulses for the walking velocity range of 0.8 $m \cdot s^{-1}$ to 1.6 $m \cdot s^{-1}$. The estimated experimental push-off work varied from 0.19 $J \cdot kg^{-1}$ to 0.54 $J \cdot kg^{-1}$ (+184.2%), while the experimental collision work magnitude also changed from 0.06 $J \cdot kg^{-1}$ to 0.62 $J \cdot kg^{-1}$ (10.3 fold boost, Figure 2A). Accordingly, the estimated experimental push-off and collision impulses ranged from 0.61 $m \cdot s^{-1}$ to 1.04 $m \cdot s^{-1}$ (70.5%) and from 0.34 $m \cdot s^{-1}$ to 1.11 $m \cdot s^{-1}$ (226.5%, Figure 2B). The walking velocity at which the push-off and collision works were equal estimated to be 1.35 $m \cdot s^{-1}$. The experimental push-off impulse and work associated with this walking speed were estimated to be 0.90 $m \cdot s^{-1}$ and 0.41 $J \cdot kg^{-1}$, respectively. They matched 0.55 $m \cdot s^{-1}$ and 0.15 $J \cdot kg^{-1}$ for the analytical optimal push-off impulse and its work at. Over the range of the examined walking speeds, the analytical optimum push-off impulse also varied from 0.25 $m \cdot s^{-1}$ to 0.70 $m \cdot s^{-1}$ (180%) when its work ranged from 0.03 $J \cdot kg^{-1}$ to 0.24 $J \cdot kg^{-1}$ (700%) for the given walking velocity range (Figure 2C & D).

For the walking speed of v = 1.35 $m \cdot s^{-1}$, we also performed an additional analysis to evaluate the effect of the delayed push-off. It was assumed that a random push-off was exerted as a fraction of the nominal push-off; the trajectories for random push-off work, random collision impulse, and work, and the required compensation after the step-to-step transition were provided in Figure 2E & F. When the push-off impulse grew from zero to 0.56 $m \cdot s^{-1}$ (optimal push-off), the collision impulse ranged from 0.96 $m \cdot s^{-1}$ to 0.56 $m \cdot s^{-1}$ (-41.6%). The push-off work rose to 0.16 $J \cdot kg^{-1}$ as collision work shrunk from 0.46 $J \cdot kg^{-1}$ to 0.16 $J \cdot kg^{-1}$ (-65.2%). The post-transition compensation also dropped from 0.46 $J \cdot kg^{-1}$ to zero.

Discussion:

GRF analysis is the simplest approach to study human walking (Park and Kim 2022). The GRF profiles are affected by walking conditions since humans modulate their walking by exerting forces and performing mechanical work (Arthur D. Kuo, Donelan, and Ruina 2005). The walking velocity affects the vertical GRF profile, boosting or shrinking its peaks' magnitudes. Since we did not have a mechanical point of view why its peaks amplitudes change at different rates, we decided to evaluate the experimental push-off and collision works for different walking velocities to examine their trends and associated impulses and reach a mechanistic understanding.

Human walking is transitioning from one inverted pendulum to the next. It is done by push-off (trailing leg) and collision impulse (leading leg) inducements simultaneously (Donelan, Kram, and Kuo 2002b). Push-off redirects the down-coming COM velocity upward (Adamczyk and Kuo 2009), during which the walker's mechanical energy is elevated. Therefore, it limits the consecutive collision work, that is, to adjust the COM velocity and its motion for the new stance further (Arthur D. Kuo 2002; Arthur D. Kuo, Donelan, and Ruina 2005). If the push-off equals the optimum magnitude, it entirely neutralizes the following dissipation (Arthur D. Kuo 2002), whereas a larger push-off shrinks the next collision dissipation further (A. D. Kuo 2001). The walker accelerates if another mechanism does not absorb the extra active work (Doke, Donelan, and Kuo 2005). The reverse is true when push-off work is less than the collision work (Figure 3).

At velocities less than $v = 1.35\ \mathrm{m} \cdot \mathrm{s}^{-1}$, we observe larger push-offs than the associated collisions. Since the average walking velocity is maintained, the excess mechanical energy most likely energizes the rebound phase, in which the lower limbs swing, and the stance leg is straightened (Arthur D. Kuo, Donelan, and Ruina 2005). As the double support phase increases (as a fraction of the stance time) with the slower walking velocity (Williams and Martin 2019), the push-off

work is likely exerted over a longer period (Arthur D. Kuo, Donelan, and Ruina 2005). Hence, it is conceivable not to detect grossly large second peaks at lower walking velocities. Likewise, we assumed the same time duration and magnitudes for push-off and collision impulses at v = 1.35 $m \cdot s^{-1}$. Thus, we expect to observe somewhat symmetrical average vertical GRF profiles (Arthur D. Kuo 2002). On the other hand, if the push-off is less than the optimal, the following collision dissipation grows. The maximum dissipation happens when the push-off is zero. Therefore, under any circumstance, if the generated push-off cannot provide the entire mechanical energy of the gait, it is plausible to assume the push-off is suboptimal and thus expect larger dissipations in the associated step (Figure 3B).

It is suggested that the push-off is almost generated by the ankle joint (Arthur D. Kuo, Donelan, and Ruina 2005). Schwartz et al. (Schwartz, Rozumalski, and Trost 2008) have reported that the ankle peak power grows with walking velocity increase. Nevertheless, there might be a walking velocity (kinetic energy) threshold in which the ankle might not be able to produce the necessary mechanical active work. As such, the remainder of the energy must be provided by the other joints, such as the hip (Arthur D. Kuo 2002; Voloshina et al. 2013). The experimental COM power trajectory indicates that such positive energy exertion must occur during the midflight (rebound) phase (Figure 1B) and after the step-to-step transition's completion. Figure 2A exhibits that collision work outpaces the push-off work past the walking speed of v = 1.35 $m \cdot s^{-1}$. Hence, it is plausible to expect the vertical GRF first peak to outgrow the second peak (Figure 1A).

In conclusion, if the push-off completely energizes the step-to-step transition, its collision dissipation is confined. However, suppose the ankle joint cannot produce the needed mechanical active work (e.g. biomechanical capacity limit), the push-off magnitude is suboptimal, and the following collision dissipation rises to create a further energy imbalance. Therefore, the associated

vertical GRF trajectory depicts such imbalance as peaks with different amplitudes. With the same token, any other challenging walking condition that prohibits the ankle push-off work generation must also exhibit vertical GRF peaks of different amplitudes. Understanding the mechanical implications of the GRF trajectory peaks is important since unequal peaks may indicate that legs have to endure large collisions that might overstress the limbs. Additionally, as post transition positive energy inducement becomes necessary, other joints have to compensate for the needed energy by over actuation that might lead to enhanced joint deterioration as such (e.g. hip).

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Figures

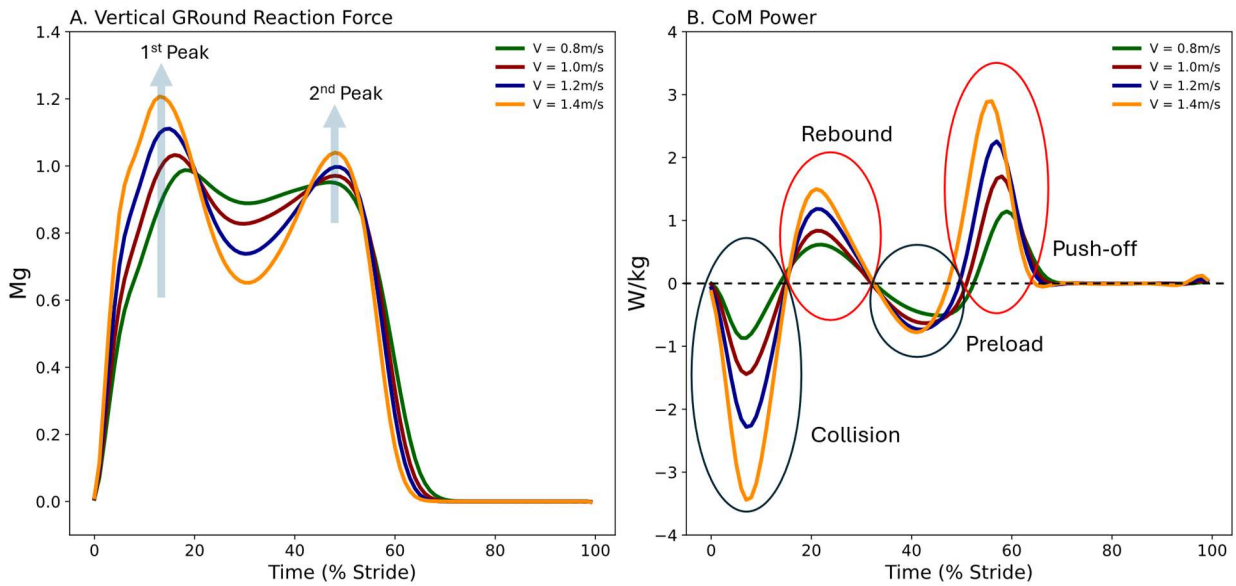

Figure 1: (A) the average trajectories of vertical GRF and (B) the average COM power trajectories for different walking velocities for young adults. As walking speed increased, the vertical GRF's first and second peaks altered at distinct rates, generating dissimilar impulses (collision and push-off).

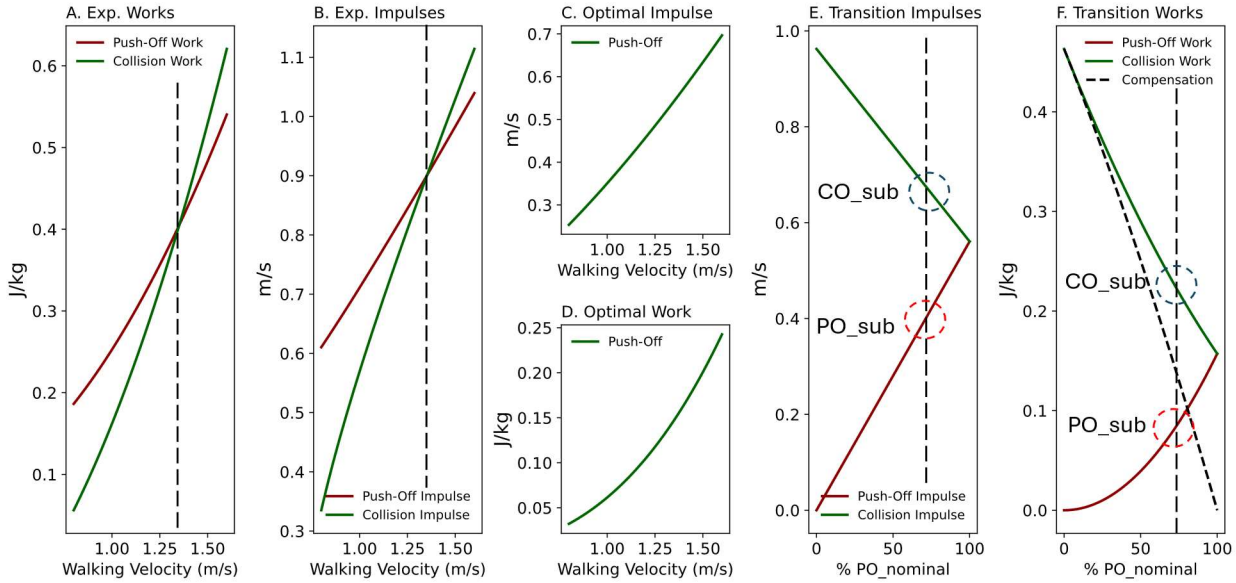

Figure 2: The step-to-step transition impulses and associated works: (A) estimated push-off and collision work trajectories based on the experimental data. The vertical dashed line indicates the walking speed at which push-off and collision are equal. (B)

estimated push-off and collision impulse trajectories based on the experimental COM works, (C) estimated analytical optimal push-off impulse, (D) estimated analytical optimal push-off work, (E) analytical collision impulses for random push-offs; po_sub indicates a suboptimal push-off impulse that co_sub is its associated collision impulse and (F) analytical collision works for random push-off works; PO_sub designates a suboptimal push-off work that CO_sub is its associated collision work.

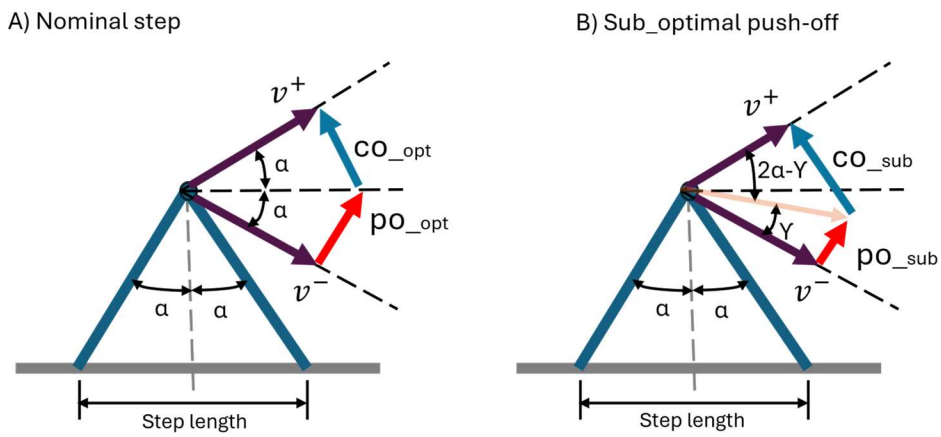

Figure 3: Schematics representing the push-off and collision for the step-to-step transition. (A) when push-off is optimal and energizes the entire transition (push-off = collision). (B) when the push-off is suboptimal and does not provide all the necessary energy for the transition and as such the subsequent collision dissipation grows.

Tables:

Table 1: Statistical analysis results using the linear mixed models on COM work components magnitudes for walking velocity variations. The significant parameters are identified by asterisks (*). With walking velocity, push-off and collision magnitudes increased significantly. Vision indicates that subjects had a view of the coming treadmill belt.

	Push-off work			Collision work	
	Gains	P_values		Gains	P_values
Intercept*	0.0546	8.06E-05	**Intercept***	0.1104	6.39E-08
Vision*	0.0137	4.22E-03	**Vision***	0.0216	2.23E-03
Velocity*	0.1844	4.04E-96	**Velocity***	-0.2940	2.57E-112