Center of Mass Work Components May Offer Estimates for Preferred Walking Speeds for Any Walking Conditions.

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Conflict of Interest: None

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Abstract:

It is suggested that preferred walking speeds coincide with the minimum metabolic energy expenditure. Since the positive step work performed on the center of mass (COM) broadly represents walking energetics, at the preferred walking speed, the positive step work must also be minimized. Positive step work is exerted at the beginning of the step (push-off) and during the stance phase (rebound), each followed by associated mechanical energy dissipation. A simple walking model suggests that the best walking economy is achieved when the entire step's active work is provided by the push-off, making the rebound merely the release of stored mechanical energy in tendons to swing the limbs. Accordingly, we propose a criterion where the preferred walking speed is when the rebound work does not energize COM motion and is completely absorbed by subsequent negative work (preload). We developed preferred walking speed trajectories for different terrain amplitudes, considering the influence of age and state of lookahead. We estimated that with normal lookahead, the preferred walking speed for young adults would be $1.22\ \mathrm{m} \cdot \mathrm{s}^{-1}$. As walking conditions became more challenging (e.g., due to age, restricted lookahead, etc.), our estimated preferred walking speeds also declined.

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Keywords: Center of mass mechanical work, preferred walking speed, walking energetics, step-to-step transition

Introduction:

One of the main objectives of walking is to keep energy expenditures at minimum [1] while other task-specific targets are also met [2]. It is suggested that the energetic expenditure is minimized when humans walk at a nominal or preferred walking speed [3]. Traditionally, the preferred walking speed is defined when the cost of transport is minimum [4]. It means walking faster or slower than the preferred walking speed increases the energetic cost of walking [5]. To determine the average preferred walking speed based on walking energetics, subjects must walk at different velocities when their energetics are measured [6]. The walking velocity that coincides with the minimum of the derived parabolic cost of transport trajectory is introduced as the preferred walking speed [5]. Since it is proposed that the active COM works at the step-to-step transition is a close representation of the metabolic walking rate [7], there must also be a mechanical equivalent approach to estimate the preferred walking speed based on the COM mechanical work.

The walking economy is hypothesized to be maximized if a pre-emptive push-off energizes the gait progression [8]. The push-off changes the direction of the prior step's COM velocity upward, as the subsequent collision adjusts the altered COM velocity to match the new stance (Figure 1A) [9]. As such, the push-off adds mechanical energy to the system while the collision dissipates it [8].

If push-off is suboptimal, it only partially energizes the gait. Therefore, the partially adjusted COM velocity in the middle of the step-to-step transition faces a larger collision dissipation to change its trajectory for the next stance (Figure 1B). Hence, the outcome velocity is smaller after the transition [8]. Therefore, further mechanical active work inducement is necessary. Otherwise, the COM velocity drops drastically, or the gait is not sustainable.

The extra compensation is suggested to be exerted during the mid-flight at the rebound phase [10]. Donelan et al. [7] have suggested that the rebound is a passive work that is released by or stored in tendons and tissues in nominal walking. As such, it is proposed that the positive energy of the rebound is absorbed during the preload. If the rebound is to energize the COM progression, its magnitude must exceed the preload [7], [8], [10]. Hence, it is plausible to assume that walking deviates from the preferred regime when push-off is less than collision or rebound is more than preload.

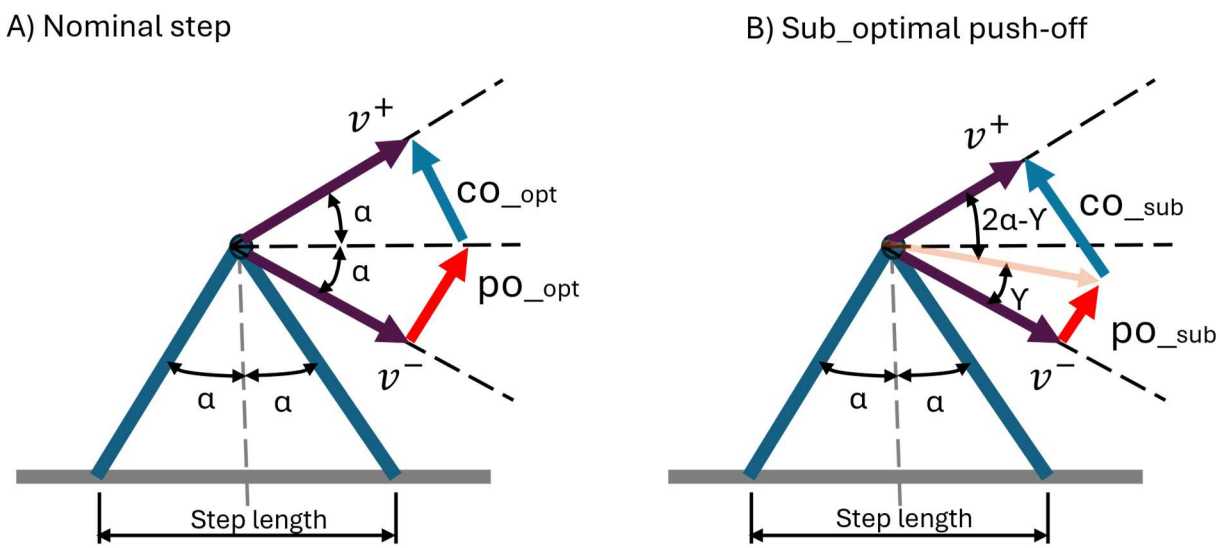

Figure 1: The step-to-step transition work exertions: (A) the optimal work exertion approach in which the push-off provides the entire active mechanical energy needed. The following collision work equals the optimal push-off, and the system's energy stays the same. (B) the suboptimal push-off creates a larger collision dissipation. As such, the system's power declines, and additional energy inducement is needed after the step-to-step transition.

Uneven walking is a case in which the push-off may deviate from optimal walking. For instance, the heel strike may happen sooner than expected [11], especially without visual information about the coming terrain [12]. Therefore, the collision occurs when the prior push-off does not completely adjust the COM velocity [9], [10]. As such, the collision magnitude grows and must be canceled by an extra active energy inducement [12], most likely by the hip torque exertion [8], [13]. Age and the state of lookahead may also affect the biomechanics of walking [12], [14].

Accordingly, we propose that for any walking condition, there is a walking velocity at which the COM mechanical works, and thus, its energetics are minimal. We assume that the best walking economy happens when only push-off provides all the required walking energy. Therefore, the rebound is only to straighten the stance leg and swing the limbs completely absorbed by the negative preload work. Since, during the uneven walking, each step's COM elevation change is unknown, we cannot estimate the optimum push-off as the summation of step dissipation and the work against gravity. As such, we propose "rebound work equal to preload" as the criterion for the preferred walking velocity instead.

Materials and Methods:

We organized experiments to study uneven walking in young and older adults. For this purpose, we modified the instrumented treadmill to use uneven terrains. We fabricated uneven terrains by gluing construction foams to the surfaces of conventional treadmill belts [13]. We furnished the same elevation profiles for 0.3 m to enable flat foot landing or with a small incline. Each terrain was identified by its maximum foam height (terrain amplitude: h). The terrains were open-ended and wrapped around the existing belts. We tightened the original and uneven terrains together (Figure 2A).

To control the subjects' lookahead horizon, we positioned them 0.7 m and 1.2 m from the front end of the treadmill (restricted and normal lookaheads, respectively, Figure 2B & C). To maintain position, the subject kept gentle contact with a surgical tube mounted by two tripods.

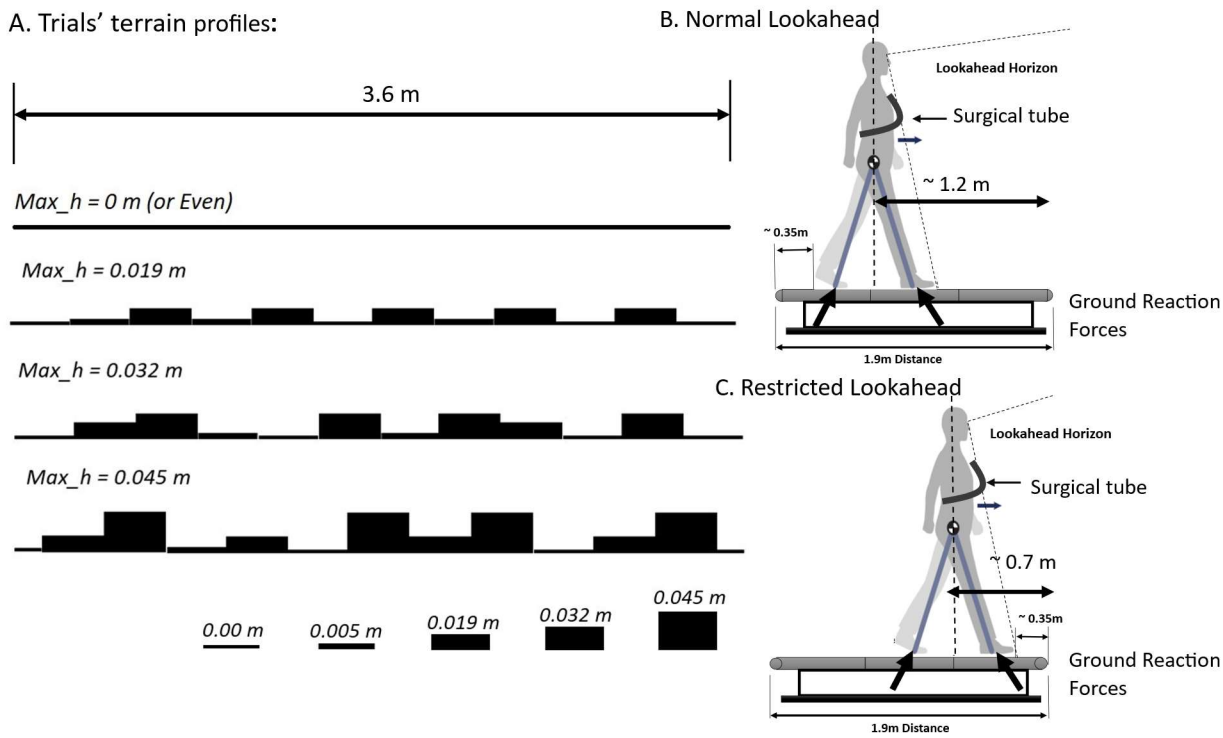

Figure 2: Uneven walking experiments setups: (A) The test terrain profiles for the uneven walking experiment. Each terrain was identified by its maximum foam height. (B) position for the normal lookahead, (C) position for the restricted lookahead.

The GRF data was collected for 60 seconds at 960 Hz and converted to forces and moments using Collins et al. [15] method. We randomized the order of the walking speeds and terrain amplitudes for each subject. The trials' velocities varied from 0.8 $\mathrm{m \cdot s^{-1}}$ to 1.4 $\mathrm{m \cdot s^{-1}}$ whereas the terrain amplitudes altered from 0 m (Even) to 0.045 m. The GRFs were filtered by a third-order zero-phase Butterworth filter (cut-off 10Hz). We used the methods presented by Donelan et al. [7] and Kuo et al. [10] to calculate the COM velocity, COM power trajectory, and stance phases' works (Figure 3).

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, terrain complexity, age, and state of lookahead (vision) were independent variables (continuous or categorical). Regression gains and associated p-values were reported to show the relationships and significance. Further, the COM work

components' statistical results were used to estimate the COM work components' trajectories for walking velocities ranging from 0.8 $\mathrm{m \cdot s^{-1}}$ to 1.6 $\mathrm{m \cdot s^{-1}}$. We defined the mid-stance positive and negative works (rebound and preload) as the difference of total positive work and push-off, and difference of total negative work and collision, respectively [10]. Since it is suggested that the energetics of walking vary $v^{3.42}$ [8], h^2 [16], we also utilized the same convention ($\dot{W} \sim v^3$ or $W \sim v^2$ and $W \sim h^2$) to perform regression analysis.

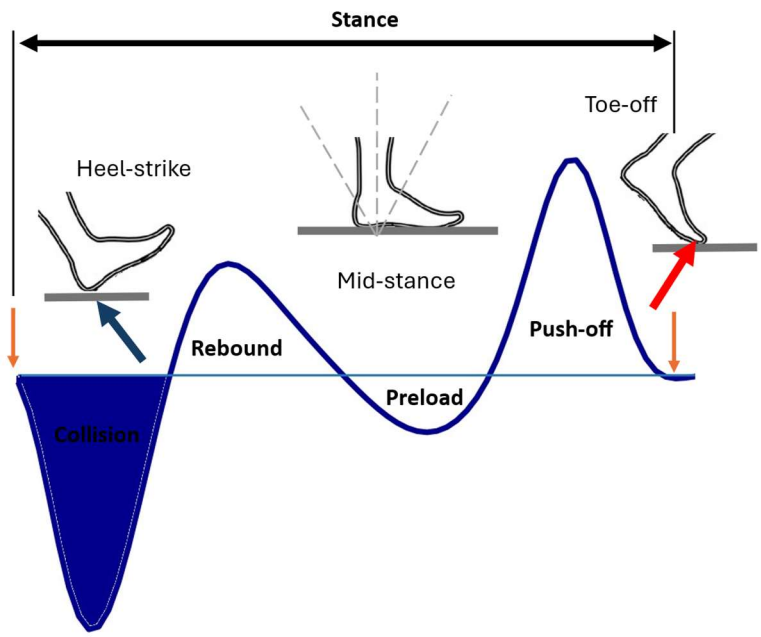

Figure 3: Typical COM power trajectory for a walking stride. It distinctly shows four phases: collision, rebound (mid-flight positive work), preload, and push-off.

We invited two groups of healthy adults to participate in our experiment: Young Adults (YA, age: 27.69 ± 5.21, mass: 71.0 ± 6.16 kg, six females and four males) and Older Adults (OA, age: 66.1 ± 1.44, mass: 77.34 ± 12.13 kg, six males and four females). The University of Calgary Conjoint Health Research Ethics Board approved the procedure (REB17-0761), and subjects provided written informed consent before the experiments. The subjects were given a few short trials to become familiar with the experimental conditions.

We defined four categories to estimate the preferred walking velocities when terrain amplitudes ranged from zero (Even) to 0.045 m: young adults with normal lookahead, young adults with restricted lookahead, older adults with normal lookahead, and older adults with restricted lookahead. COM work profiles were developed for each category and terrain amplitude as walking velocity varied from 0.8 $m \cdot s^{-1}$ to 1.6 $m \cdot s^{-1}$.

Results:

The COM work components altered significantly with parameters of interest (Table 1). The estimated COM work trajectories for young adults with normal lookahead were generated as the base case (Figure 4A). The estimated preferred walking velocities for young adults with normal lookahead based on "push-off = collision" and "rebound = collision" were 1.35 $m \cdot s^{-1}$ and 1.22 $m \cdot s^{-1}$, respectively (difference = 10.7%).

There were amplitudes for the set trial ranges for which no preferred walking velocity was estimated. For those amplitudes, this meant the rebound was always larger than the preload (Figure 4B). As such, we also reported the range of the terrain amplitudes in which preferred walking speeds were detected.

We fitted second-order polynomials to each category's estimated preferred walking velocities with increasing terrain amplitude. For young adults with normal lookahead, the preferred walking velocity ranged from 1.22 $m \cdot s^{-1}$ to 0.87 $m \cdot s^{-1}$ as terrain amplitudes rose from zero to 0.035 m (-28.1%, p = 4.4e-9, R^2=0.998). Likewise, for young adults with restricted lookahead, the preferred walking velocities were estimated to vary from 1.13 $m \cdot s^{-1}$ to 0.88 $m \cdot s^{-1}$ (-22.1%, p = 1.3e-8, R^2=0.999) as the terrain amplitude upper bound was 0.3 m. The older adults' terrain amplitude ranges also differed based on the state of the lookahead. With the normal lookahead, their terrain

amplitude ranged from zero to 0.02 m as their preferred walking speeds were from 0.95 $m \cdot s^{-1}$ to 0.85 $m \cdot s^{-1}$ (-10.5%, p = 0.999, R^2=2.2e-5). With the restricted lookaheads, their terrain amplitudes were only from zero to 0.015 m and the associated preferred walking speed declined from 0.9 $m \cdot s^{-1}$ to 0.83 $m \cdot s^{-1}$ (-7.78%, p = 1.7e-3, R^2=0.997).

Table 1: The statistical analysis result summary for COM work components using linear mixed effect model ($W = c_1 + c_2 \cdot v^2 + c_3 \cdot h^2 + c_4 \cdot C(vision) + c_5 \cdot C(age)$). The significant parameters are identified by an asterisk (*).

	Average Positive Work Gains	P_values		Average Negative Work Gains	P_values
Intercept*	0.0594	2.26E-02	**Intercept***	-0.0649	7.77E-03
Vision*	-0.0199	2.77E-02	**Vision***	0.0321	1.45E-04
Age	0.0368	3.10E-01	**Age**	-0.0237	4.86E-01
Velocity*	0.3182	2.38E-81	**Velocity***	-0.2948	1.22E-79
Velocity-Age	-0.0085	7.17E-01	**Velocity-Age**	-0.0206	3.51E-01
Max_h*	60.0450	3.24E-08	**Max_h***	-55.8683	3.95E-08
Max_h-Age*	30.6408	4.61E-02	**Max_h-Age***	-28.4014	4.83E-02
R^2	0.6422		***R^2***	0.6625	
	Average Push-Off			**Average Collision**	
Intercept*	0.0546	8.06E-05	**Intercept***	0.1104	6.39E-08
Vision*	0.0137	4.22E-03	**Vision***	0.0216	2.23E-03
Age	-0.0243	2.07E-01	**Age**	0.0346	2.24E-01
Velocity*	0.1844	4.04E-96	**Velocity***	-0.2940	2.57E-112
Velocity-Age*	-0.0283	2.41E-02	**Velocity-Age***	-0.0505	6.26E-03
Max_h*	-15.8506	6.10E-03	**Max_h***	-54.1978	1.92E-10
Max_h-Age	4.3133	5.98E-01	**Max_h-Age***	-21.8911	6.90E-02
R^2	0.4903		***R^2***	0.7766	

Discussion:

The preferred walking velocity is suggested to coincide with the minimum transport cost for a given walking task or condition [2]. It is proposed that the best walking economy also happens when the push-off provides all the walking energy pre-emptively [8]. However, estimating the optimal push-offs for various walking conditions is impossible. An instance is uneven walking in which humans' elevations change frequently; therefore, they need to perform work against gravity

of random magnitudes [17]. It is also reported that with normal lookahead, humans tend to distribute the required active work among several steps [18], [19], [20]. As such, A certain step's exerted push-off may be elevated beyond what is needed. Consequently, we have attempted to verify the preferred walking velocity by detecting the instance where the rebound work is passive and completely consumed by the preload phase.

During even walking as the COM elevation does not change, the two preferred walking speed estimations ('push-off = collision' and 'rebound = preload') must yield similar results. However, we observe that the 'push-off = collision' always yields a larger estimate (Figure 4A). If we assume this criterion, the associated 'rebound – preload' is more than zero. Therefore, during the stance phase, extra positive mechanical work is added to the COM. Since during the stance phase, the COM motion resembles an inverted pendulum which is conservative, its velocity must increase. It is contrary to treadmill walking in which the average walking velocity is constant.

For preferred walking speed estimation, if we assumed 'rebound = preload', the associated 'push-off – collision' is greater than zero (Figure 4A). Nevertheless, this excess energy might be wasted in another form. The simple model of walking [8] assumes that the push-off is exerted entirely pre-emptively. However, in reality, a portion of push-off is delayed, which is exerted after the subsequent heel strike [10] which is also true for smooth treadmill walking [9]. Since during the double support, the stance leg is switched, the COM motion base changes [8]. As such, a portion of the delayed push-off might be wasted by stretching the stance leg perpendicular to the COM motion trajectory (Figure 5A & B). Most likely, the wasted push-off converts to heat [21]. This perhaps also explains the positive difference of total positive and negative work for the examined walking speed range. Defining the *Adjusted Push-off* by deducting the difference of total positive and negative work from the push-off work, we observe that 'adjusted push-off = collision' also

yield estimated preferred walking speed similar to ‘rebound = preload’. Hence, it might further support using ‘preload = rebound’ to predict the preferred walking speeds.

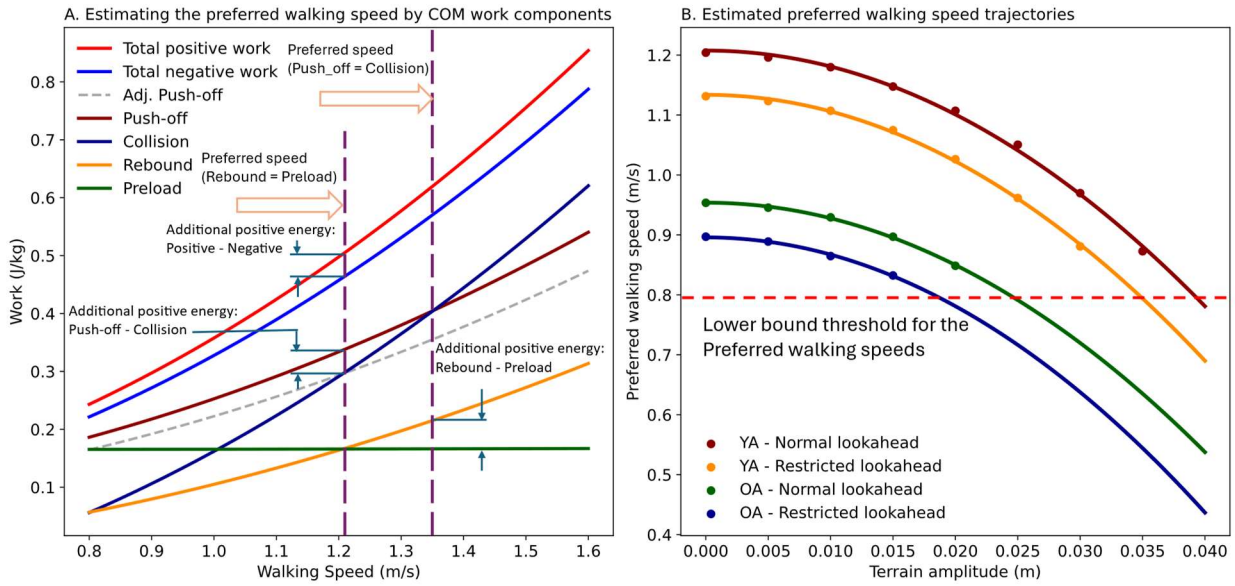

Figure 4: (A) The young adults' COM work components for even walking with normal lookahead. The crossing points at which the collision or rebound surpassed the push-off or preload was assumed to represent the preferred walking velocity at which the entire energy of the step-to-step transition was provided pre-emptively. (B) The estimated preferred walking velocity trajectories when terrain complexities increased from zero (even) to 0.045 m. The trajectories indicated terrain amplitude thresholds for each category beyond which the pre-emptive active energy inducement was insufficient to energize the step-to-step transition. Therefore, the rebound work exceeded preload for the entire velocity range ($0.8\ m \cdot s^{-1}$ to $1.6\ m \cdot s^{-1}$). Some speed estimations were also very low to sustain human walking. Therefore, a lower bound must have been set to filter them out.

The estimated preferred walking velocity for even walking is comparable with the available reports for young and older adults [4], [22]. One finding is the influence of the state of the lookahead during the even walking. It is conceivable to assume that visual information enables humans to select a foothold that maximizes the kinetic energy extraction [12] or regulates the relative timing of the push-offs and collisions to exert push-offs pre-emptively [11], [18], [19]. However, it is plausible to assume that vision's influence on even walking should be minimal. Our experimental results, however, suggest that relying on flight time (vestibular and proprioceptive) or tactile is less accurate than vision to regulate the gait. It aligns with reports showing that humans with impaired sight tend to walk slower [23] and backs the effect of vision on human walking [24], [25].

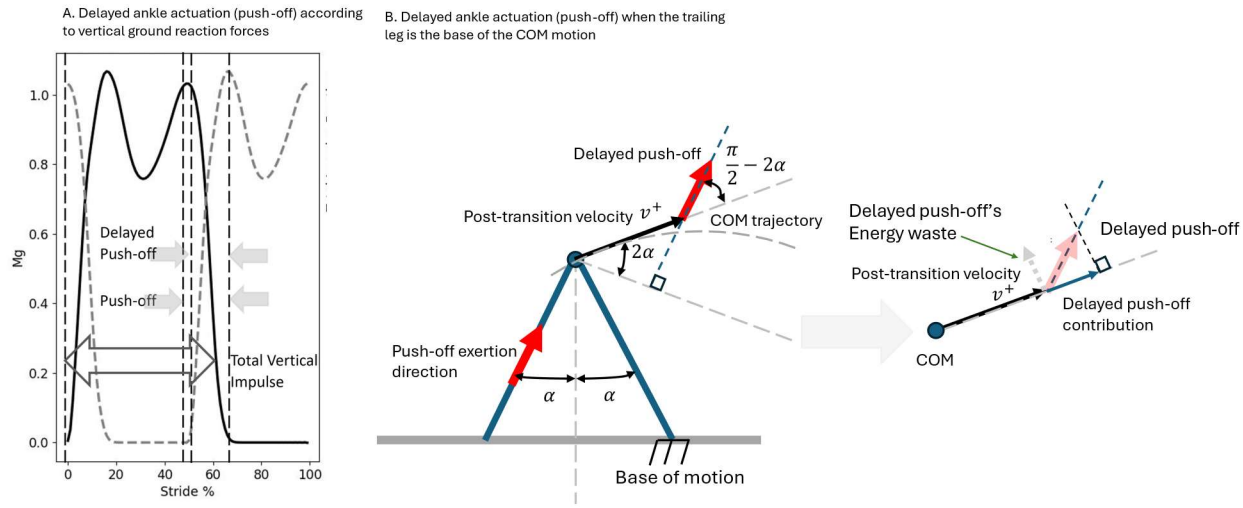

Figure 5: (A) Even during the smooth treadmill walking a portion of the trailing lead active work (push-off) is exerted when the leading leg becomes the new stance leg (delayed). (B) the delayed push-off impulse is exerted along the trailing leg. Since after the heel strike the COM trajectory changes, a portion of the delayed push-off is wasted to stretch the stance leg perpendicular to COM motion trajectory.

Similar to reported slower preferred walking speeds for older adults, our estimated trends also suggest a material difference between young and older adults [22]. Since each category's preferred walking speed trajectory is almost entirely explained by the terrain amplitude ($R^2 > 0.99$), the decline of the estimated preferred walking velocities with the second power of the terrain amplitude may also support the suggestion that walking costs increase with the step elevation height changes quadratically [16].

Another observation is the thresholds detected for each category. After a certain terrain amplitude, there is no preferred walking velocity for which all mechanical energy is provided pre-emptively. In other words, since the ankle joint exerts the push-off [10], it is plausible to assume that either the ankle's biomechanical capacity cannot keep up with the increasing demand for the necessary active work, or during uneven walking, the ankle work exertion is interrupted. If the ankle work exertion is interrupted, it means that during uneven walking, there are circumstances in which ankle work performance is more expensive than hip torque inducement mechanically.

Likewise, some of the estimated velocities are overly low to be practically sustained during human walking. Most likely, the energetic consequences of walking at such low speeds outpace the benefit of mechanically energizing gait entirely with push-off [26]. Therefore, a threshold must be adopted to filter out projected speeds that are lower than the threshold. For instance, walking velocities less than $0.8\ \mathrm{m} \cdot \mathrm{s}^{-1}$ must not be considered.

We proposed estimating the preferred walking speed based on the center of mass (COM), as it has been suggested that step-to-step mechanical work determines most of the human walking energetics [7]. This approach aligns with the energetic cost of transport, where the primary objective of walking is to minimize metabolic cost [4]. Nevertheless, when additional factors such as time are considered [27], the determining criterion must also be adjusted. Additionally, other indicators such as walking stability and reproducibility may also contribute to refining the determination of preferred walking speed [28].

In summary, we have been able to propose a method to estimate the preferred walking velocities for the range of our experimental uneven walking study based on the COM work components. It is plausible that the same approach might be utilized to estimate the preferred walking speeds for any walking conditions or individuals by examining the associated COM work components [7]. For extreme cases (very fast or very slow velocities), the estimated velocities must be further examined to ensure that other biomechanical factors do not drastically affect the energetics of walking. If the preferred walking velocity is not detected for a specific walking condition, the push-off does not completely energize the gait. Therefore, after the step-to-step transition, extra energy inducement is required.

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