# 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:

This study investigates the role of optimal push-off impulses in minimizing the total mechanical work per step, aiming to achieve passive stance work performance for any walking conditions. By optimizing push-offs to cover the entire step's energy demands, the stance work may become only storage and release of mechanical energy through tendons and tissues. Our simulations indicate that for each walking speed, there is an optimal push-off impulse that ensures energy balance without the need for additional energy input or dissipation during the stance phase in which the soft tissue dissipation is negligible, resulting in reduced total positive work performance. In even terrain, the estimated preferred walking speeds align closely with literature values for young adults (~ $1.25\ \mathrm{m.s^{-1}}$) and older adults (~ $1.10\ \mathrm{m.s^{-1}}$), with a reduction observed for the restricted lookahead (15%). For uneven walking, terrain amplitude was shown to impact walking costs quadratically, with optimal speeds declining by approximately 20% per unit increase in terrain amplitude. Key findings include evidence that net stance work remains near zero when push-off optimally covers collision and gravity work, confirming the passive nature of stance work under these conditions. We also observed that the preferred speeds for older adults tend to be 12-15% lower than for younger adults, likely due to biomechanical adaptations. Beyond certain terrain amplitudes, no preferred walking speed allowed fully passive stance work, highlighting a possible biomechanical threshold where ankle push-off alone becomes insufficient and hip torque compensation may be necessary. This approach provides a framework for estimating preferred walking speeds across different terrain amplitudes (continuous parameter), varying conditions and demographics, with potential applications in designing assistive devices and gait rehabilitation protocols that reduce metabolic cost through optimal mechanical work management.


**Word Count:**


**Keywords:** Optimal Push-Off Impulse, Passive Stance Work, Mechanical Work Minimization, Preferred Walking Speed, Uneven Terrain Locomotion

## Introduction:

One primary objective of walking is to minimize energy expenditure [1] while simultaneously achieving other task-specific goals [2]. Research suggests that energy expenditure is minimized when humans walk at a nominal or preferred walking speed [3]. The preferred walking speed is traditionally defined as the speed at which the cost of transport is minimized [4]; walking faster or slower than this speed results in increased energetic costs [5]. To determine an individual's average preferred walking speed based on energetics, subjects are often asked to walk at various velocities while their energy expenditure is measured [6]. The walking speed that coincides with the minimum of the resulting parabolic cost of transport curve is identified as the preferred walking speed [5]. Since it has been proposed that the active center of mass (COM) work during step-to-step transitions closely represents metabolic walking rates [7], a mechanical approach may also estimate preferred walking speed based on COM mechanical work.

It is hypothesized that walking economy is optimized when a pre-emptive push-off energizes gait progression [8]. The push-off redirects the COM velocity from the previous step upward, allowing the subsequent collision to adjust the COM velocity to match the new stance (Figure 1A) [9]. Consequently, 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, leading to greater collision dissipation at mid-transition to adjust the COM trajectory for the next stance (Figure 1B). This results in a reduced outcome velocity after the transition [8], requiring additional active mechanical work to maintain the gait. If not, the COM velocity will decline significantly, and the gait may become unsustainable. This extra compensatory work is suggested to occur during the mid-flight rebound phase [9], [10]. Similarly, if push-off exceeds the subsequent heel-strike collision, the post-transition velocity increases, requiring energy dissipation during the subsequent stance phase to

maintain average velocity. This dissipation must occur as negative work during the stance (preload).

It is also proposed that the rebound phase in nominal walking operates as passive work stored and released by tendons and tissues [9], [11]. Thus, the positive energy generated by the rebound phase is absorbed during the preload [9]. The total power contributions of the leg joints during the single support phase (rigid body) when the COM motion resembles an inverted pendulum [12] have been shown to balance rebound and preload in nominal walking with minimal soft tissue dissipation [13]. To counteract deficits from push-off and collision [10], if the rebound is to energize the COM progression, it must exceed the preload; conversely, if dissipation is required, preload must exceed rebound. Hence, it is plausible that walking deviates from the preferred regime when push-off and collision (even walking), or rebound and preload magnitudes, are unequal.

Uneven walking presents a case where push-off may deviate from optimal patterns (Figure 1C). For example, heel strike may occur earlier than expected [14], especially without visual cues about upcoming terrain [15]. In such cases, the collision occurs before the prior push-off fully adjusts the COM velocity [9], [16], increasing the collision magnitude and necessitating additional active energy input [15], likely through hip torque exertion [8], [17]. Age and lookahead state also influence walking biomechanics [15], [18]. Thus, we propose that for any walking conditions, a walking speed exists at which COM mechanical work is optimized. Based on a powered simplest walking model, we hypothesize that, in the mechanically optimal regime for any walking condition, push-off requiring active muscle work provides all necessary walking energy. Consequently, rebound serves only to straighten the stance leg and swing the limbs [9] and is fully absorbed by the negative preload work, remaining passive [9], [11].

Since the COM elevation change for each step is unknown during uneven walking, it is challenging to estimate the optimal push-off as the sum of step dissipation and gravitational work covering the total mechanical work required per step. We therefore propose "rebound work equal to preload"—where work is passive—as a criterion for preferred walking speed instead.

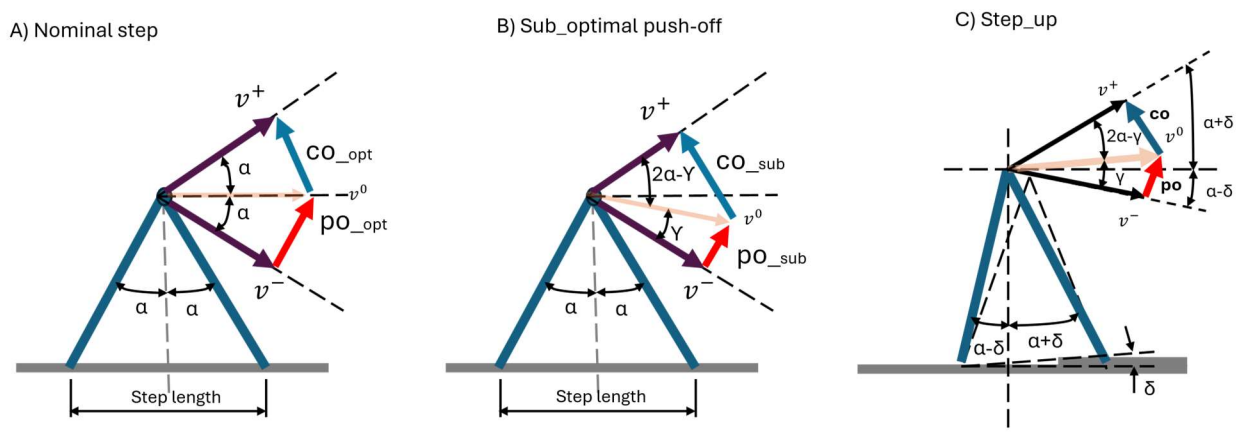


Figure 1: The step-to-step transition is when the stance leg is switched. (A) During a nominal walking, the push-off work is exerted pre-emptively and is equal to the subsequent collision. (B) If a sub-optimal push-off is exerted, the subsequent collision magnitude grows. The reverse is true when the push-off is more than the nominal magnitude (C) Uneven walking is a deviation from nominal even walking. In ideal case, the pre-emptive push-off must provide the mechanical energy for step change and gravity work.

# Materials and Methods:

## Simulation:

Building on the powered simple walking model [8], we compute the analytical collision dissipation when push-off is suboptimal (a fraction of the nominal push-off). As shown in Figure 1B, the velocity prior to transition is approximated by the average velocity ($v_{ave}$) and '2α' represents the leading and trailing leg angles at the point of transition [8]. The suboptimal push-off ($po_{sub}$) modifies the pre-transition COM velocity ($v_{ave}$) by the angle of '$\gamma$' which is less than 'α':

$$\gamma = \text{atan}\left(\frac{po_{sub}}{v_{ave}}\right) \qquad \text{Equation 1}$$

With the mid-transition COM velocity denoted as $v^0$, we can estimate the collision impulse ($co$) as:

$$\begin{cases} v^0 = \dfrac{v_{ave}}{\cos(\gamma)} \\ or \\ v^0 = \dfrac{co}{\sin(2\alpha - \gamma)} \end{cases} \rightarrow co = v_{ave}\frac{\sin(2\alpha - \gamma)}{\cos(\gamma)} \qquad \text{Equation 2}$$

For uneven walking, when the walker steps up by a height $\Delta h$, the post-transition velocity ($v_{opt}^{+}$) must exceed the pre-transition velocity to compensate for the increased potential energy. Thus:

$$0.5v_{opt}^{+^2} - 0.5v_{ave}^2 = g.\Delta h \rightarrow v_{opt}^{+} = \sqrt{v_{ave}^2 + 2g.\Delta h} \qquad \text{Equation 3}$$

The step transition impulses ($u$) works are evaluated as $0.5u^2$ [14]. In the optimal scenario, where all transition work is provided by pre-emptive push-off, the transition impulses are:

$$\begin{cases} po_{opt} = v_{ave}.\tan(\gamma_{opt}) \\ co_{opt} = v_{opt}^{+}.\tan(2\alpha - \gamma_{opt}) \end{cases} \qquad \text{Equation 4}$$

If PO and CO denote push-off and collision work, respectively, their difference should match the gravitational work needed to maintain momentum:

$$PO - CO = g.\Delta h \rightarrow 0.5v_{ave}^2.\tan^2(\gamma_{opt}) - 0.5v_{opt}^{+^2}.\tan^2(2\alpha - \gamma_{opt}) = g.\Delta h \qquad \text{Equation 5}$$

We solve Equation 6 numerically to determine $\gamma_{opt}$ for given conditions. For our calculations, we assume $v_{ave} = 1.25\ \mathrm{m.s^{-1}}$, and its corresponding $\alpha = 0.35$ [11]. For uneven walking, $\Delta h = 0.025\mathrm{m}$ is used. We ran simulations for even and uneven walking where the push-off impulse varied from zero to the optimal level (Figure 2). Results were normalized by the optimal push-off work for each case.

The simulation shows that suboptimal push-off results in a mechanical energy deficit post-transition, requiring additional positive work during the stance phase [10]. For even walking, if

only 80% of optimal push-off impulse is exerted, an additional 70% of nominal push-off work must be performed after the transition, increasing total positive work to 133% of nominal. This implies 33% extra mechanical work, with a corresponding metabolic cost.

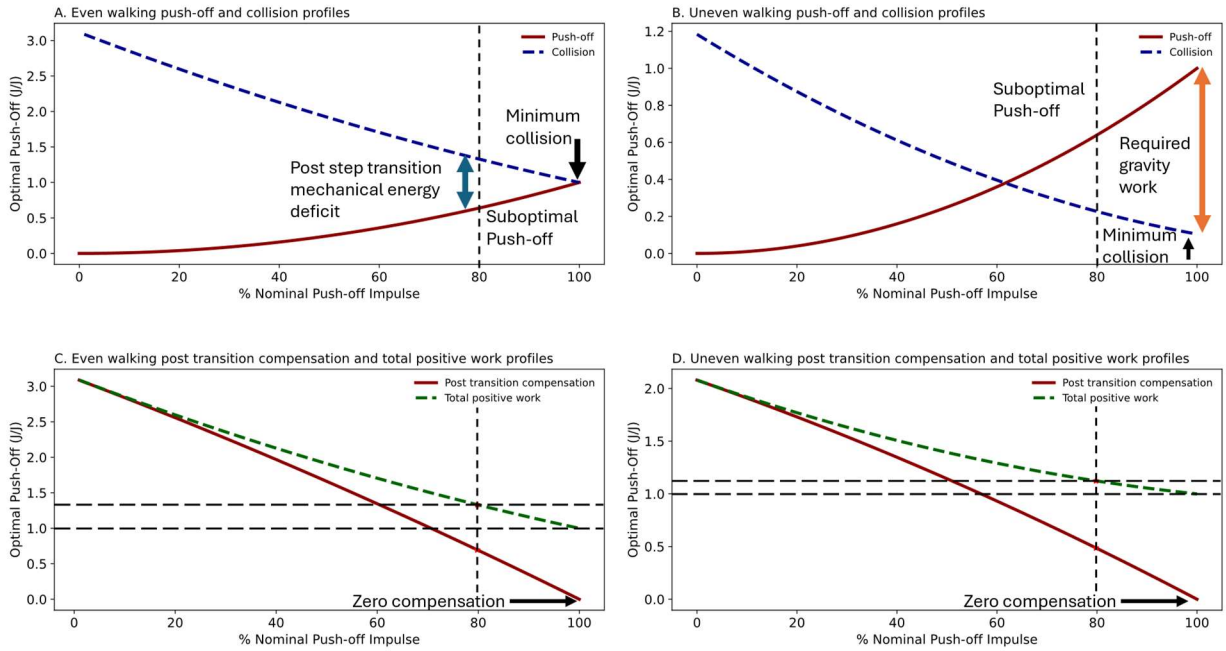


Figure 2: Simulation results when suboptimal push-off is exerted: (top row) resulted collision work trajectory during the even walking and known step up (uneven walking with know gravity work) as the exerted push-off impulse ranges from zero to nominal magnitudes, (bottom row) post transition work compensation and total positive work trajectories of suboptimal push-off impulse for even walking and known step up (uneven walking).

For $\Delta h = 0.025$m, the required gravitational work is approximately 90% of nominal push-off. With only 80% of required push-off, post-transition mechanical energy falls short by 49% of what's needed to reach the same speed at midstance, resulting in 112% of optimal work. This indicates a need for 12% additional positive work with associated metabolic consequences. The simulation suggests increased rebound work beyond what preload can absorb when pre-emptive push-off fails to cover total transition energy. Thus, when PO – CO < 0 (even walking) or PO – CO < gravity work, the push-off is suboptimal.

Conversely, if push-off exceeds the nominal value, post-transition speed surpasses the average speed (speed at midstance, Figure 3), requiring dissipation to maintain steady speed. For even walking, when push-off impulse is 125% of nominal, 91% of nominal push-off work must be dissipated. Similar excess push-off raises the required dissipation to 172% of optimal work for uneven walking. Notably, the simple powered walking model defines a maximum pre-emptive push-off $po_{max} = v_{ave}.\tan(2\alpha)$ [8].

Since mechanical energy largely accounts for walking energetics [7], and energy conservation is a fundamental walking goal [1], it can be inferred that suboptimal or excessive push-off is not favorable from an energy perspective.

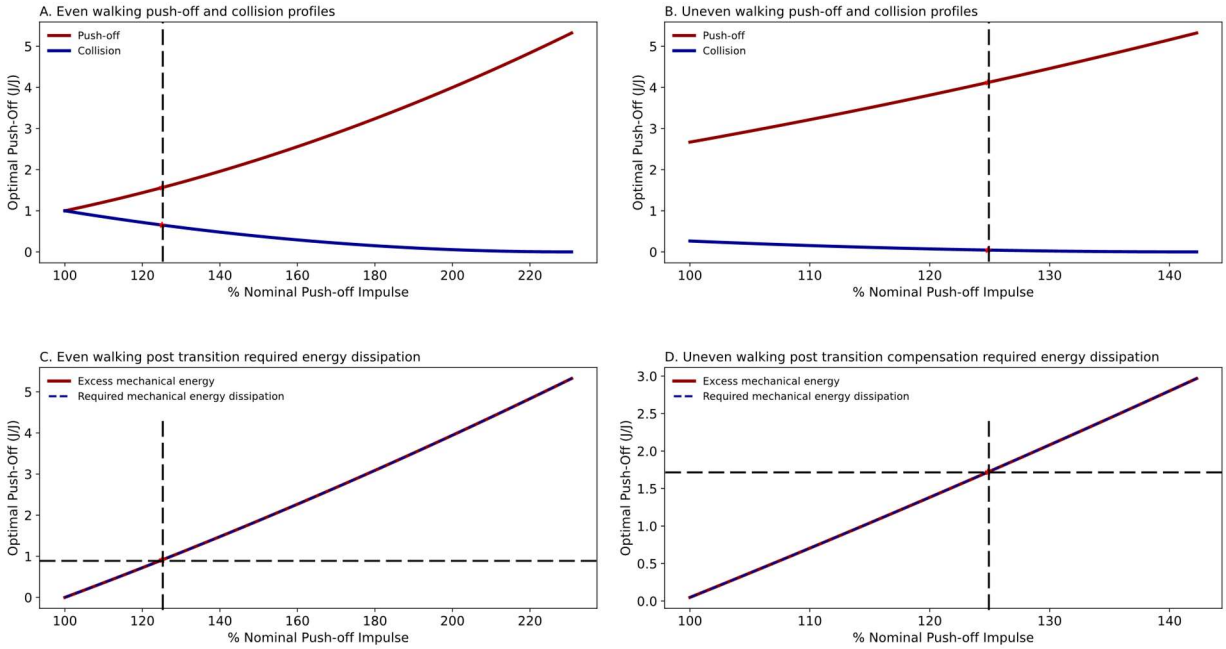


Figure 3: Simulation results for excess pre-emptive push-off: (top row) resulted collision work trajectory during the even walking and known step up (uneven walking) as the exerted push-off impulse ranges from nominal magnitude to maximum analytical amount. For maximum analytical push-off impulse the collision work becomes zeros. (Bottom row) post transition required work dissipation (excess mechanical energy) of excess push-off impulse for even walking and step up (uneven walking).

## COM work component traces based on experimental data:

Using the trajectories proposed for various walking conditions—including sate of lookahead, terrain amplitudes, and walking speeds—for both young and older adults [10], we developed COM work trajectories (Figure 4 and Table 1).

We calculated trajectories for total positive work, total negative work, push-off, and collision across walking speeds and terrain amplitudes, ranging from 0.8 $m \cdot s^{-1}$ to 1.6 $m \cdot s^{-1}$ and from 0 m to 0.06 m, respectively. Trajectories were adjusted to account for random bias in instrumented treadmill calibration. Consequently, we calculated rebound and preload values as follows: rebound as the difference between total positive work and push-off, and preload as the difference between total negative work and collision [9], [10].

Since the trajectories represented various walking conditions where the optimal push-off of each step could vary, we used the "Rebound = Preload" criterion to estimate the preferred walking speed. Additionally, we generated COM work component trajectories for even walking as a validation measure and compared the derived preferred walking speeds (for young and older adults with both normal and restricted lookahead) with values reported in the literature.

# Results:

We developed an analytical simulation based on a simple powered walking model [8] to analyze the mechanical energy demand after step-to-step transitions when the push-off does not fully meet the step transition energy requirements, whether for even walking or step ups (uneven walking). The simulation suggested that if push-off does not offset the subsequent collision (in either even or uneven walking) or account for gravitational work (in uneven walking), a mechanical energy

deficit will arise post-transition. This deficit must be compensated during the following stance phase through positive work (rebound) [7], [9].

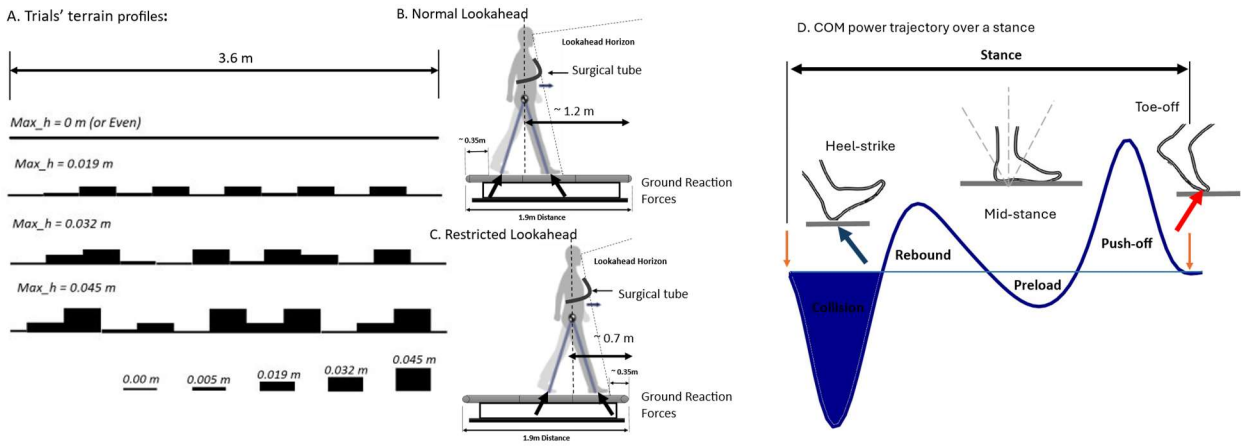


Figure 4: Uneven walking experiments setups: (A) The test terrain profiles for the uneven walking experiment. Each terrain was identified by its maximum foam height. (B) position for the normal lookahead, (C) position for the restricted lookahead. (D) Typical COM power trajectory for a walking stride. It distinctly shows four phases: collision, rebound (mid-flight positive work), preload, and push-off.

Table 1: The proposed COM work components trajectories derived by the linear mixed effect model for the experimental data. 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 | |

From this, we inferred that when push-off is suboptimal, the following rebound requires active work, demanding metabolic energy. Conversely, if push-off is optimal, the subsequent rebound contributes no extra energy to COM motion, meaning the rebound is passive and only incurs limb oscillation costs [19], [20], [21]. The simulation further indicated that if the push-off impulse exceeds the optimal level, maintaining the prescribed average walking speed and momentum requires dissipation of mechanical energy post-transition. During the stance phase, this manifests as negative work (preload) [7], [9] that absorbs the excess energy. When push-off exceeds optimal levels, the rebound is smaller than the preload, suggesting that this excess energy likely converts to heat [22] rather than being stored in limbs and tendons [9], [11]. Thus, excessive push-off results in a rebound that is not entirely passive.

Based on experimentally derived COM work component trajectories, we identified instances where rebound and preload were equal. Following simulation results, we assumed that in these cases, no additional positive compensatory work or mechanical dissipation occurred, making the associated stance mechanical works (rebound and preload) passive (storage and release). We termed the resulting walking speeds under these conditions (accounting for age, terrain, and state of lookahead) as the preferred walking speeds.

For uneven walking, certain terrain amplitudes within the trial ranges did not yield preferred walking speeds, indicating that the rebound was always greater than the preload for these amplitudes (Figure 5). We also reported the range of terrain amplitudes where preferred walking speeds were observed, noting that age and lookahead state decreased the estimated preferred walking speed.

We fitted second-order polynomials to the estimated preferred walking speeds within each category as terrain amplitude increased [23]. The preferred walking speed for young adults with

normal lookahead, where “push-off = collision” and “rebound = collision,” was 1.20 m·s⁻¹. For young adults with normal lookahead, the preferred walking velocity ranged from 1.20 m·s⁻¹ to 0.87 m·s⁻¹ as terrain amplitudes rose from 0 to 0.035 m (-28.1%, p = 4.4e-9, $R^2$=0.998).

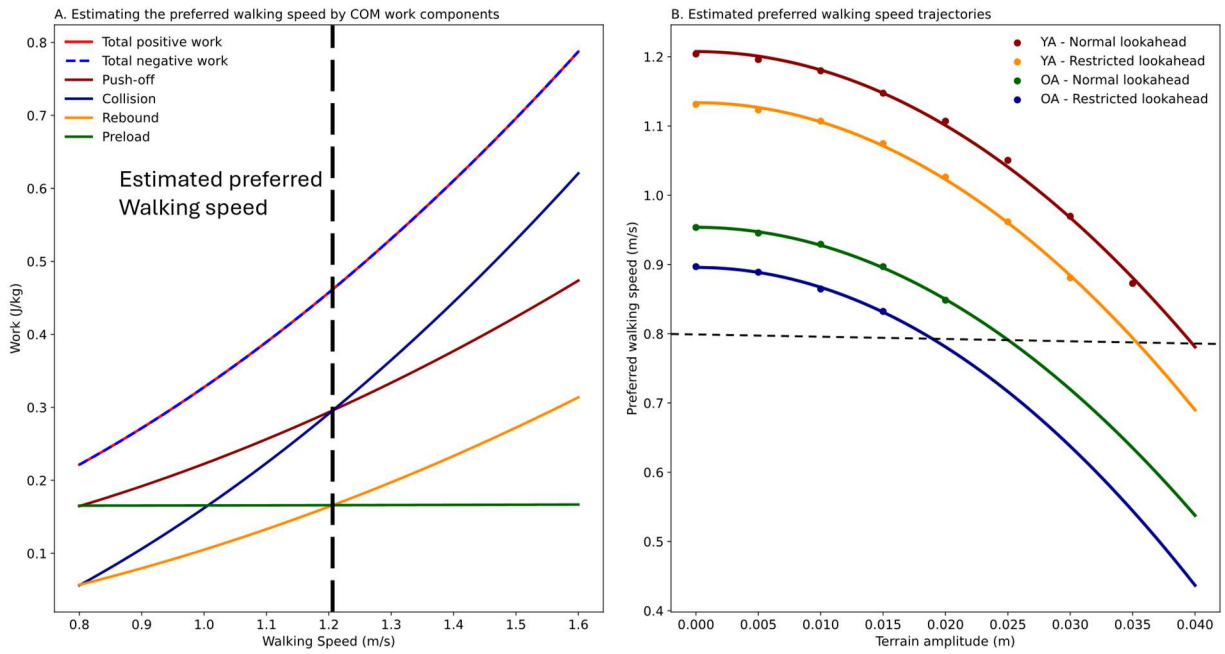


Figure 5: (A) The young adults' COM work components for even walking with normal lookahead. The crossing points at which the collision or rebound surpassed the push-off or preload was assumed to represent the preferred walking velocity at which the entire energy of the step-to-step transition was provided 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 (0.8 $m \cdot s^{-1}$) was set to filter them out.

It is documented that self-selected walking speed declines with visual impairment [24], which we also observed with restricted lookahead. For young adults with restricted lookahead, the preferred walking velocities were estimated to vary from 1.13 m·s⁻¹ to 0.88 m·s⁻¹ (-22.1%, p = 1.3e-8, $R^2$=0.999) as terrain amplitude increased to 0.3 m.

The preferred walking speed of older adults is generally lower than that of young adults, which was consistent with our estimates. Additionally, the terrain amplitude ranges for older adults varied based on state of lookahead. With normal lookahead, terrain amplitudes ranged from 0 to 0.02 m,

and preferred walking speeds declined from 0.95 $m \cdot s^{-1}$ to 0.85 $m \cdot s^{-1}$ (-10.5%, p = 2.2e-5, $R^2$=0.999). With restricted lookahead, terrain amplitudes ranged only from 0 to 0.015 m, and preferred walking speeds 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).

## Discussion:

The preferred walking velocity is believed to align with the minimum cost of transport for a given walking task or condition [2]. Optimal walking economy is suggested to occur when the push-off pre-emptively provides all the energy needed for each step [8]. Since the center of mass (COM) work accounts for most walking energetics [7], the preferred walking speed may be estimated using COM mechanical work components, including push-off. However, finding optimal push-offs for varying walking conditions can be challenging. For example, during uneven walking, where elevation changes frequently, humans must perform work against gravity with varying intensities [25]. Studies indicate that with normal lookahead, humans tend to spread the active work required across multiple steps [26], [27], [28]. Consequently, a specific step's push-off may exceed the immediate energy need, prompting us to explore alternatives to directly evaluating push-off work.

It is proposed that humans perform both positive and negative work during the single support phase [7], [9]. Given that the single support phase mimics an inverted pendulum's motion [12], assumed to be conservative, any work performed should theoretically cancel out. Otherwise, the COM would either accelerate or decelerate. It is proposed that the pre-emptive push-off is the active work that supplies the required step energy, while the single support positive and negative work phases are passive [7]. In other words, these phases primarily involve energy storage and release through tendons and tissues [7], [11]. Therefore, if the net single support work is non-zero, it likely

serves to regulate COM momentum or energy [10]. Identifying speeds where rebound work is fully offset by preload work could indicate optimal push-off work for a given walking condition.

Our simulations of step transition impulses and associated work suggest an optimal push-off impulse for each speed that fully supplies the energy needed for step transitions. For a given speed, if push-off is below optimal, additional positive mechanical energy is needed; if excessive, energy dissipation occurs post-transition. COM work components trajectories suggest that at specific speeds under different conditions (e.g., terrain amplitude, state of lookahead), stance work is not balanced, necessitating net mechanical work that regulates COM energy. For instance, when push-off is insufficient relative to collision (and gravity) work, energy is added in the next stance phase to accelerate post-transition speed. Conversely, if push-off exceeds collision and gravity work, energy is dissipated to decelerate post-transition speed. Hence, non-zero net stance work indicates non-optimal step work, signalling increased metabolic cost.

We can identify speeds at which net stance work is zero (rebound = preload), indicating push-off can offset heel-strike and gravity work. For such speeds, simulations imply no need to adjust COM speed post-transition, as soft tissue dissipation in single support (rebound and preload) is minimal [13], suggesting that stance work is passive with no metabolic cost, except potentially limb swing cost [19], [20], [21].

The estimated preferred walking speeds for even terrain align with reported values for young and older adults [2], [4], [29]. Similar to previous findings [2], preferred speeds for uneven walking are slower than even walking. Another observation is the impact of lookahead on even walking, where visual cues allow individuals to optimize foothold choices [15] and synchronize push-offs with collisions for energy-efficient steps [14], [26], [27]. Vision seems critical for accuracy, as evidenced by slower walking in visually impaired individuals [24], [30], [31].

For older adults, the slower preferred speeds match reports, and trends indicate terrain amplitude impacts speed, aligning with the quadratic increase in walking costs due to step elevation changes [23]. Moreover, thresholds emerge where no preferred speed exists to pre-emptively meet energy demands. This suggests a biomechanical limitation of the ankle, or interrupted ankle work during uneven walking, making hip torque a substitute energy source in such cases.

Some projected velocities are impractically low, suggesting that walking at such speeds might outweigh the benefit of fully energizing gait through push-off [32]. Therefore, low-speed projections, such as those below 0.8 $m \cdot s^{-1}$, should be excluded.

Our method for estimating preferred speeds is based on COM mechanics when the pre-emptive push-off is optimum that results in passive stance works. It aligns with minimizing the COM total positive work of each step that closely represents the walking energetics [4]. In our estimation we have considered the terrain amplitude as a varying continuous parameter. However, other factors like time [33], stability, and reproducibility could refine this criterion [34]. In conclusion, Although the simple powered model cannot directly determine a preferred walking speed, it can offer valuable insights into whether a particular walking regime is mechanically optimal. Our approach estimates preferred speeds based on COM work trajectories from uneven walking data [10], potentially extendable to other conditions by analyzing associated COM work components [7]. In extreme cases (very fast or slow speeds), biomechanical factors should be examined to ensure walking energetics remain optimal. If no preferred speed is found, it most likely indicates that additional energy is required post-transition, indicating that push-off alone does not fully energize gait.

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