The Powered Simplest Walking Model Modifies the Rate of Recovery Definition

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Conflict of Interest: None

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Abstract:

Humans aim to minimize their walking energy expenditure. As walking mechanical work demands a metabolic cost, minimizing mechanical work performance may limit the metabolic cost of walking. As such, it is suggested that humans conserve a portion of each step's mechanical energy, transferring it to the next step, known as the rate of recovery. Previous definitions assumed human walking to be conservative as an inverted pendulum, requiring extra mechanical energy infusion when potential to kinetic energy conversion was upset. However, as human walking grossly deviates from pendular motion during step-to-step transitions, we proposed a new definition based on mechanical energy dissipation of each transition. Analytical simulation depicted rates of recovery exceeding 80%, with rates over 50% for young adults with normal lookahead based on the experimental data, surpassing previous suggestions. Both analytical and experimental results showed declining trends with velocity, indicating the new definition did not designate preferred walking speeds. Simulation also revealed that reducing pre-emptive push-off magnitude aligned with declined rates of recovery. Reversing the preferred order of push-off and collision almost halved the rate of recovery. Experimental results demonstrated that age, restricted lookahead, and terrain complexity (amplitude increase) lowered the rate of recovery, consistent with prior reports of increased energetics cost of walking under these conditions.

Introduction:

Humans tend to optimize the metabolic energy needed for walking [4]. Besides other purposes, metabolic energy is used to perform mechanical work on the Center of Mass (COM). This mechanical work propels the COM forward and counteracts mechanical energy losses. Therefore, conserving mechanical energy during walking could also decrease the metabolic cost [8]. However, it's noted that mechanical energy is sometimes wasted during human walking [10]. Specifically, during the transition between steps, energy is dissipated at heel-strike [1]. This dissipation during step transitions may redefine the concept of rate of recovery, where the legs' external work compensates for the energy lost at heel-strike [8, 14]. Furthermore, factors like age, state of lookahead, walking speed, and terrain likely impact human performance and, consequently, the rate of recovery during walking.

Human locomotion is proposed to mimic pendulum and spring-like motion to minimize the active work of muscles [4]. Specifically, the single support phase of human walking aligns with the motion of an inverted pendulum [15]. In this context, if there's no dissipation, external energy inputs are not necessary when a walker begins locomotion with sufficient initial energy. Thus, human work performances essentially entail converting potential and kinetic energies within a conservative system.

According to Cavagna et al. [4], walkers perform work against gravity (W_v) to lift and accelerate the COM forward (W_f). They contend that when potential and kinetic energies are completely out of phase, no dissipation occurs as there's a full energy exchange. Put simply, converting gravitational potential into kinetic energy, propels the walker forward. However, when these energies begin to align, mechanical energy exchange is disrupted, leading to dissipation. Consequently, humans exert external COM work (W_{ext}) to compensate for this lost energy. This argument is premised on the assumption that human walking involves no other energy wastes.

Considering that the right and left legs can be viewed as separate actuators, each contributing toe-off and heel-strike impulses [14], investigating their effects on the human COM is reasonable. Similar to other

mechanical linear actuators, the work of each leg is determined by the force applied multiplied by the corresponding displacement. Thus, the mechanical work of each leg cannot simply cancel out the other leg's work performance mathematically. In other words, while the net outcome may resemble of the resultant force, the independent work generation of each leg involves separate energetic costs [11].

Both toe-off and heel-strike impulses exert an upward force on the COM in the frontal plane. However, their effects differ in the sagittal plane. The toe-off impulse propels the pelvis in the direction of progression. On the other hand, the heel-strike impulse opposes the progression direction, leading to partial waste of momentum and mechanical energy (Figure 1A & B) [8, 10, 14]. Consequently, the toe-off impulse is referred to as the push-off, emphasizing its contribution to forward momentum, while the heel-strike impulse is termed the collision, highlighting its dissipative nature [14]. As a result, push-off actively increases the mechanical energy of the walker, whereas collision dissipates it [15].

Donelan et al. [10] have hypothesized that humans simultaneously perform positive and negative work at the step-to-step transition point. This implies a significant disruption to the inverted pendulum motion characteristic of human walking as the transition occurs from one pendulum-like motion to the next. Additionally, Donelan et al. [8] proposed that such simultaneous COM works are mechanically costly and can serve as a close indicator of walking energetics. Therefore, it implies that the external COM work is not induced due to the undermining of kinetic energy and potential energy conversions. Rather, it is a consequence of the energy dissipation occurring at the step-to-step transition.

The proposed model for demonstrating powered step-to-step progression illustrates steady-state walking without acceleration or deceleration, aligning with the preferred walking speed [14]. Consequently, the magnitudes of push-off and collision are equal [10]. However, certain walking conditions can compromise the optimal exertion of push-off. For instance, when heel-strike occurs sooner than anticipated [6], the pre-emptive push-off may restrict the magnitude of collision dissipation [14]. Consequently, the delayed push-off must compensate for the remaining dissipation after the step-to-step transition and supply

additional mechanical energy to maintain the subsequent gait. Thus, introducing a random pre-emptive push-off with sub-optimal magnitude is expected to coincide with lower rates of recovery since dissipation increases. Age, state of lookahead, and terrain complexity can all influence human walking, affecting the required COM mechanical work and, consequently, the rate of recovery. Given that walking energetics increase with terrain complexity [20, 22] and age [7], we anticipate lower associated rates of recovery. Furthermore, with restricted lookahead, humans may struggle to select appropriate footholds and may not fully benefit from the inherent dynamics of human walking [18]. Hence, we expect the rate of recovery also to be adversely affected with the restricted lookahead.

New Definition for Rate of Recovery:

According to a powered simplest walking model [14], the active push-off is applied to COM pre-emptively to mechanically energize the transition [5]. Therefore, the push-off work represents the external work required to compensate for dissipation (W_{ext}) [4]. If we regard the total mechanical energy of the human body as a combination of potential and kinetic energies ($E_{tot} = E_P + E_K$), and we assume the two extremes of a stance where the COM is at its lowest point as the reference for gravitational potential energy during steady walking ($E_P = 0$), then at the end of a stance phase, the kinetic energy is at its maximum and is equal to the total energy.

Assuming that the COM velocity before the transition equals the average walking velocity [14], to maintain steady walking, this energy must be conserved after the step-to-step transition (active work energy addition = heel-strike energy dissipation, or push-off (PO) = collision (CO)). Therefore, the rate of recovery can be expressed as follows:

$$Rate\ of\ Recovery = \frac{\frac{1}{2}v_{ave}^2 - PO}{\frac{1}{2}v_{ave}^2} \qquad \text{Eq. 1}$$

The nominal push-off impulse is $po = v_{ave} \cdot \tan\alpha$ (Figure 1C & D); therefore, the nominal push-off work becomes $PO = \frac{1}{2}v_{ave}^2 \cdot \tan^2\alpha$ [14]. With the small angle approximation, they become: $po = v_{ave} \cdot \alpha$ and

$PO = \frac{1}{2}v_{ave}^2 \cdot \alpha^2$. Besides, the step length (s) is proportional to 2α [14], and the step length for a given walking speed follows a power law: $s \sim v^{0.42}$ [12]. Therefore, $2\alpha = c \cdot v^{0.42}$; hence $\alpha = \frac{1}{2}c \cdot v^{0.42}$. It modifies the push-off and its works as $po = \frac{1}{2}c \cdot v_{ave}^{1.42}$ and $PO = \frac{1}{8}c^2 \cdot v_{ave}^{2.84}$. Accordingly, the recovery turns into:

$$Rate\ of\ Recovery_{theoretical} = \frac{\frac{1}{2}v_{ave}^2 - \frac{1}{8}c^2 \cdot v_{ave}^{2.84}}{\frac{1}{2}v_{ave}^2} = 1 - \frac{1}{4}c^2 \cdot v_{ave}^{0.84} \quad \text{Eq. 2}$$

Defining the dissipation with the same approach to push-off, it becomes:

$$Dissipation = \frac{1}{4}c^2 \cdot v_{ave}^{0.84} \quad \text{Eq. 3}$$

Utilizing the principals of powered simplest walking model to a random push-off exertion [14] and considering it as a fraction of the nominal push-off, the mid-transition velocity (v^0) creates an arbitrary angle with the COM velocity before transition (v^-). It is calculated by $\gamma = \arctan(\frac{po_{rand}}{v_{ave}})$. As $v^- \sim v_{ave}$ [14], the transition collision impulse turns into:

$$co = v_{ave} \cdot \sin 2\alpha - po_{rand} \cdot \cos 2\alpha \quad \text{Eq. 4}$$

Considering the dissipation work to be equal to the step-to-step transition ($CO = 0.5co^2$), the rate of recovery is calculated as:

$$Rate\ of\ Recovery_{theoretical} = \frac{\frac{1}{2}v_{ave}^2 - \mathrm{CO}}{\frac{1}{2}v_{ave}^2} = 1 - (\sin 2\alpha - \left(\frac{po_{rand}}{v_{ave}}\right) \cdot \cos 2\alpha)^2 \quad \text{Eq. 5}$$

Likewise, for the experimental data, the rare of recovery can be derived from:

$$Rate\ of\ Recovery_{experimental} = \frac{\frac{1}{2}v_{ave}^2 - CO_{exp}}{\frac{1}{2}v_{ave}^2} = 1 - \frac{2CO_{exp}}{v_{ave}^2} \quad \text{Eq. 6}$$

Materials and Methods:

We conducted experimental trials to investigate uneven walking in both young and older adults. To emulate uneven terrains, we modified the instrumented treadmill. The uneven terrains were created by attaching construction foams to the belts of recreational treadmills using construction adhesives. These

terrains were designed to be open-ended and were wrapped around the existing belts. When the lacing pins of the uneven terrains were secured, both the original belt and the uneven terrains were re-tensioned simultaneously. Each terrain was characterized by the maximum height of its foams (Max_h: 0 (even), 0.019m, 0.032m, and 0.045m, Figure 2A) [22].

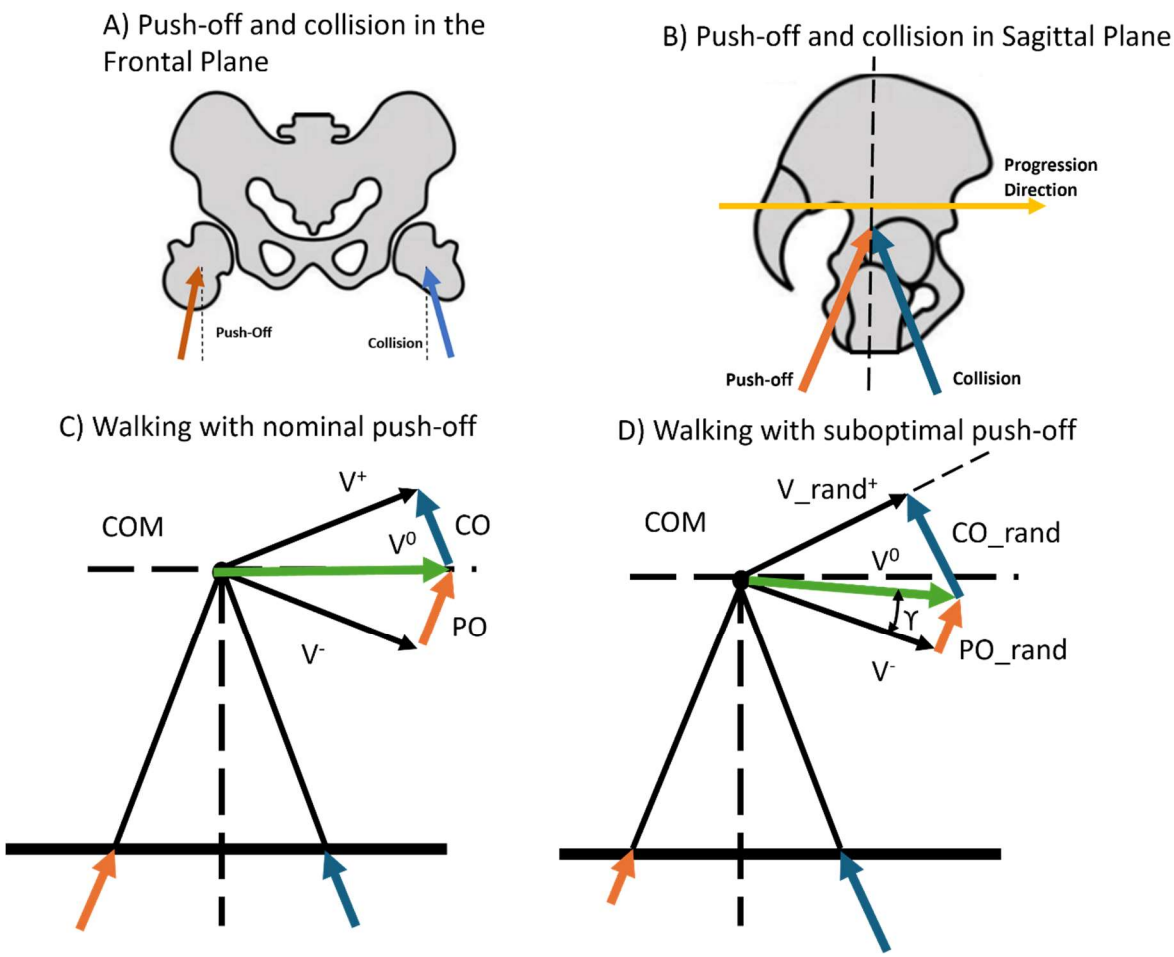

Figure 1: Schematics showing the step-to-step transition during even walking (A) push-off and collision impulses have similar effects on the COM in the vertical direction, (B) push-off adds to the COM mechanical energy in the progression direction while collision reduces the momentum. (C) In nominal walking, the push-off and collision works are equal, (D) if the pre-emptive push-off is less than optimal (random magnitude), the magnitude of the subsequent collision grows and the post transition velocity declines.

The ground reaction force (GRF) data were collected for 60 seconds at a sampling rate of 960 Hz [5]. The order of the walking experiments was randomized for each subject. The trials included velocities ranging from 0.8 $\mathrm{m} \cdot \mathrm{s}^{-1}$ to 1.4 $\mathrm{m} \cdot \mathrm{s}^{-1}$, and terrain amplitudes (peak to peak heights) increased from zero (representing even walking) to 0.045 m. The schedule of the trials is provided in Table 1.

Table 1: The uneven walking trials schedules showing the trials walking velocity and terrain amplitude ranges. The 'ya/Ya' stands for young adults and 'oa/OA' stands for older adults. The upper-case letters are for trials with normal lookahead, and the lower-case letters are for the restricted lookahead tests.

Terrains Amplitudes (m) / Trials Velocities (m/s)	0	0.019	0.032	0.045
0.8			oa-ya/ YA-OA	
1			oa-ya/ YA-OA	
1.2	oa-ya/ YA-OA	oa-ya/ YA-OA	oa-ya/ YA-OA	oa-ya/ YA-OA
1.4			oa-ya/ YA-OA	

To control the subjects' state of lookaheads, we positioned them 0.7m or 1.2m from the front end of the treadmill (restricted and normal lookaheads, Figure 2B & C). Subjects maintained their position by keeping a gentle touch with a surgical tube mounted by two tripods across the treadmill.

The GRFs were filtered using a third-order zero-phase Butterworth filter with a cutoff frequency of 10 Hz. We applied the methods outlined by Donelan et al. [9] and Kuo et al. [16] to compute the COM velocity, COM power trajectory, and the works during stance phases. The dissipation due to heel strike collision was determined by integrating the collision power trajectory over time (Figure 3) [16].

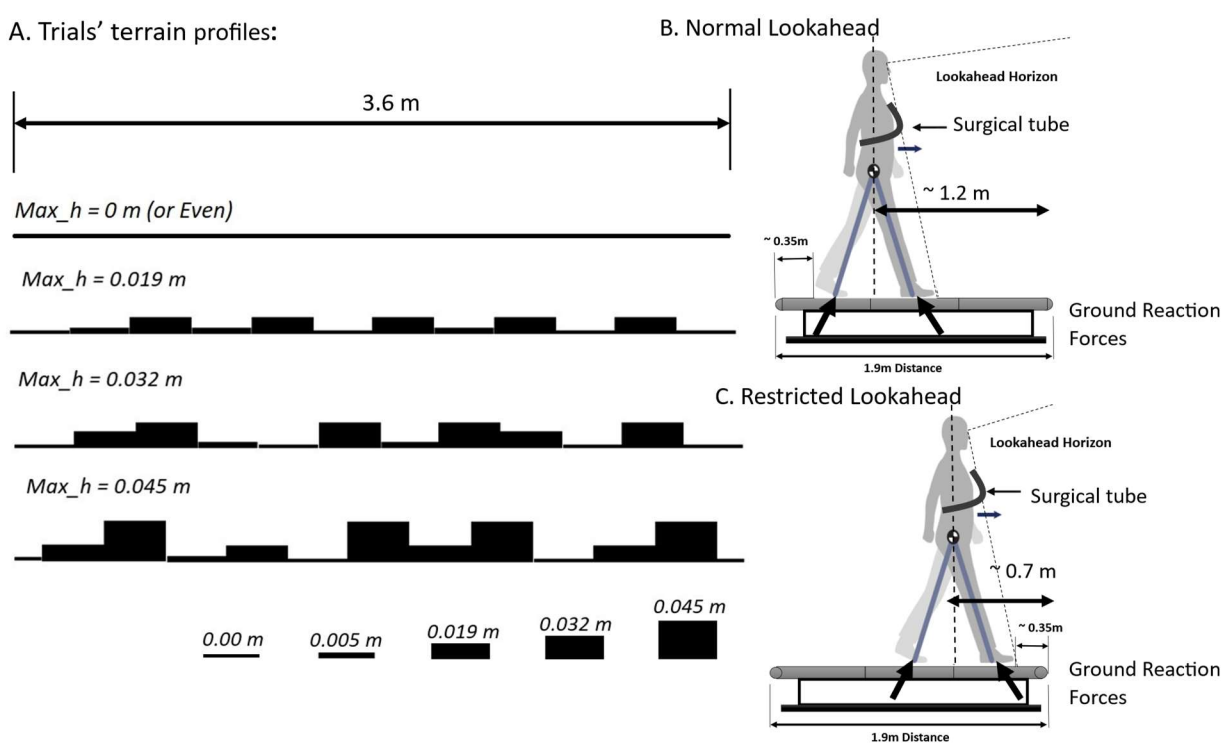

Figure 2: Uneven walking experiments settings: 9A) the uneven terrains wrapped around the existing terrain belt, (B) walking with normal lookahead at which subjects had almost two steps of unobstructed view of the coming terrain, (C) restricted look ahead at which subjects were positioned in the front of treadmill to have limited view of the coming terrain.

To assess the impact of age, we recruited two groups of healthy adults to participate in our experiment: Young Adults and Older Adults. The young adults had an average age of 27.69 ± 5.21 years and an average mass of 71.0 ± 6.16 kg, consisting of six females and four males. The older adults had an average age of 66.1 ± 1.44 years and an average mass of 77.34 ± 12.13 kg, with six males and four females. The University of Calgary Conjoint Health Research Ethics Board approved the procedure, and all subjects provided written informed consent prior to participating in the experiments. Before the formal trials, subjects were given a few short trials to familiarize themselves with the experimental conditions.

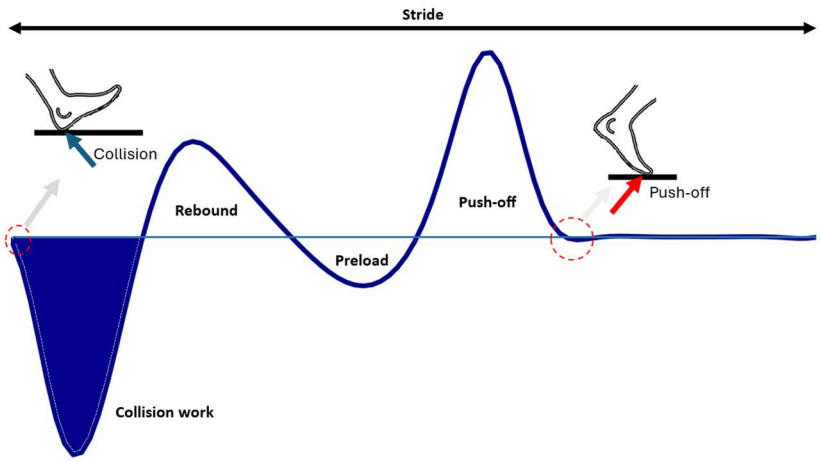

Figure 3: Center of mass (COM) power trajectory during a stride. At heel strike, the COM performs a large negative work known as collision which dissipated the COM mechanical energy.

For statistical analysis, we employed linear regression analysis using Linear Mixed Effects Models (Statsmodels 0.15.0). The collision dissipation and the rate of recovery served as the dependent variables. Independent variables included trials' walking velocity, terrain amplitude, age, and state of lookahead (continuous and categorical). The regression coefficients (gains) and associated p-values were reported to elucidate relationships and significance levels. Given suggestions that walking energetics (rate) may vary with v^3 [14] and h^2 (terrain amplitude) [23], we followed a comparable convention for our regression analysis ($\mathrm{CO} \sim \mathrm{v}^2$, $\mathrm{Rate\ of\ Recovery} \sim \mathrm{v}^2$, $\mathrm{CO} \sim \mathrm{h}^2$, and $\mathrm{Rate\ of\ Recovery} \sim \mathrm{h}^2$).

Results:

We attempted to redefine the rate of recovery based on the step-to-step mechanical work dissipation [9], during which the COM trajectory deviates significantly from conservative inverted pendulum motion. Firstly, we estimated the analytical rate of recovery based on a powered simplest walking model [13], considering nominal and random push-off impulses (analytical). Additionally, we utilized the results from our experiments on uneven walking (COM collision work dissipations) to derive the human walking rate of recovery under various walking conditions (age, state of lookahead, speed, and terrain amplitude) to assess their impact. We ensured appropriate units for the investigated parameters; however, we reported the rate of recovery as the fraction of the total COM mechanical energy.

We estimated the step length using the empirical power law for any given velocity [12]. As the walking velocity increased from 0.8 $\mathrm{m} \cdot \mathrm{s}^{-1}$ to 1.6 $\mathrm{m} \cdot \mathrm{s}^{-1}$, the step length varied from 0.61 rad to 0.82 rad, representing a 34.4% increase. Simultaneously, the analytical total energy of walking (COM kinetic energy just before the transition) and the push-off work during the step-to-step transition also increased substantially, by 400% (from 0.32 $\mathrm{J} \cdot \mathrm{kg}^{-1}$ to 1.28 $\mathrm{J} \cdot \mathrm{kg}^{-1}$) and 733.3% (from 0.03 $\mathrm{J} \cdot \mathrm{kg}^{-1}$ to 0.22 $\mathrm{J} \cdot \mathrm{kg}^{-1}$), respectively. However, the rate of recovery declined from 90.6% to 83.1%, representing an 8.3% decrease. Figure 4 illustrates the variations in walking biomechanical features of interest with walking velocity.

For the random push-off inducement, as it varied from zero to the nominal magnitude for a given velocity (v = 1.25 $\mathrm{m} \cdot \mathrm{s}^{-1}$, and α = 0.37 rad), the mid-transition velocity angle with respect to the pre-transition velocity changed from zero to 0.37 rad. Similarly, the analytical collision impulse decreased from 0.84 $\mathrm{m} \cdot \mathrm{s}^{-1}$ to 0.49 $\mathrm{m} \cdot \mathrm{s}^{-1}$ (a reduction of 71.4%). In contrast, the analytical push-off work increased from zero to 0.12 $\mathrm{J} \cdot \mathrm{kg}^{-1}$, while the magnitude of analytical collision work decreased from 0.36 $\mathrm{J} \cdot \mathrm{kg}^{-1}$ to 0.12 $\mathrm{J} \cdot \mathrm{kg}^{-1}$ (a reduction of 66.7%). Moreover, the modified rate of recovery increased from 54.5% to 84.9% (an increase of 55.8%, Figure 5).

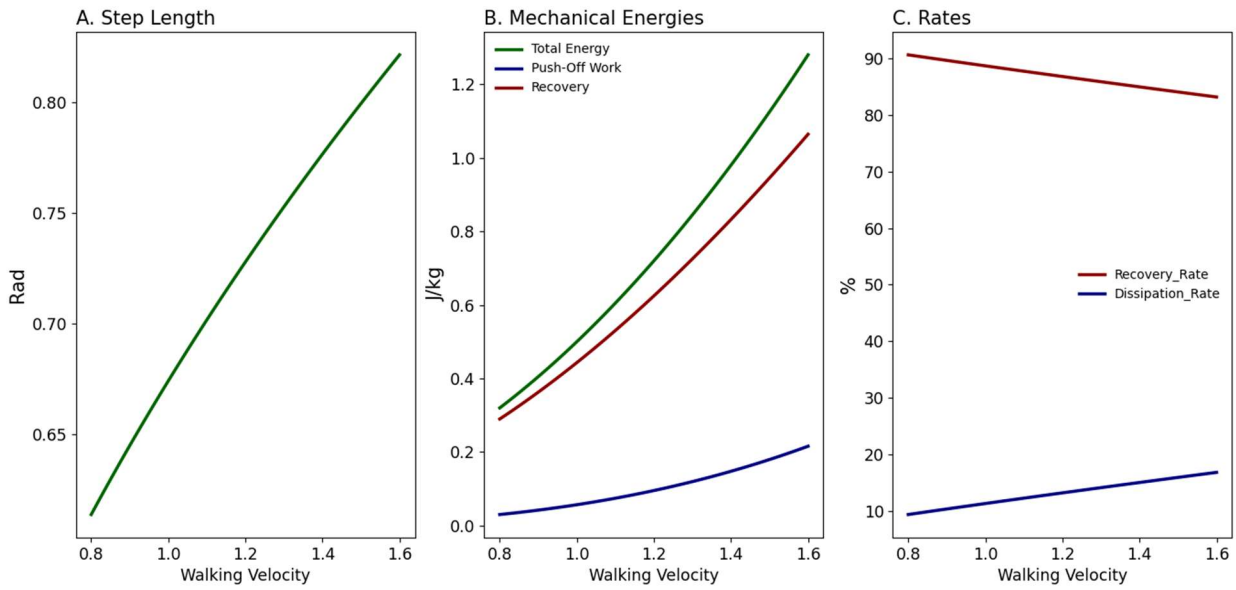

Figure 4: Summary of analytics simulation: with the walking velocity increase (A) the step length also increased, (B) the total walker's mechanical energy, push-off work and the magnitude of the mechanical energy transferred from one step to the next (recovery) increased, (C) while the dissipation rate rose, the rate of recovery declined.

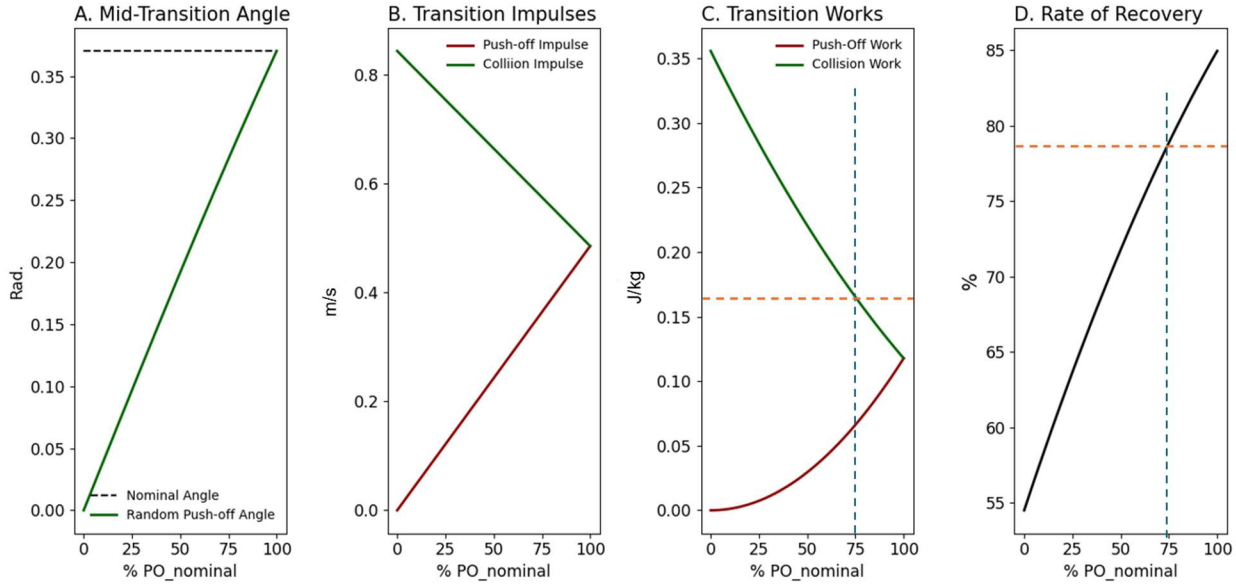

Figure 5: With a random push-off exertion (less than nominal magnitude): (A) the mid-transition velocity angle with pre-transition velocity rose, (B) resulted collision impulse declined, (C) the associated collision work dissipation decreased, (D) the modified rate of recovery for the suboptimal push-off elevated. The dashed line depicts exerting 75% of the optimal push-off. The associated transition dissipation is 0.17 $J \cdot kg^{-1}$ and the estimated rate of recovery is 78%.

The magnitude of heel strike dissipation (collision) did not exhibit significant changes with age. However, its magnitude decreased with normal lookahead (vision: -0.02 $\mathrm{J} \cdot \mathrm{kg}^{-1}$). Conversely, with the other investigated factors, the collision magnitude increased (negative gains for the negative value). Specifically,

with velocity, the rate of collision increase was -0.18 $\mathrm{J \cdot kg^{-1} \cdot v^2}$, while the interaction of age and walking speed slightly amplified it (-0.03 $\mathrm{J \cdot kg^{-1} \cdot v^2}$: 16.7%). Furthermore, as the terrain amplitude increased, the collision magnitude rose by -52.45 $\mathrm{J \cdot kg^{-1} \cdot m^2}$. Notably, the interaction of age and terrain amplitude further heightened the variation rate (-22.18 $\mathrm{J \cdot kg^{-1} \cdot m^2}$: 42.3%, Figure 6 and Table 2).

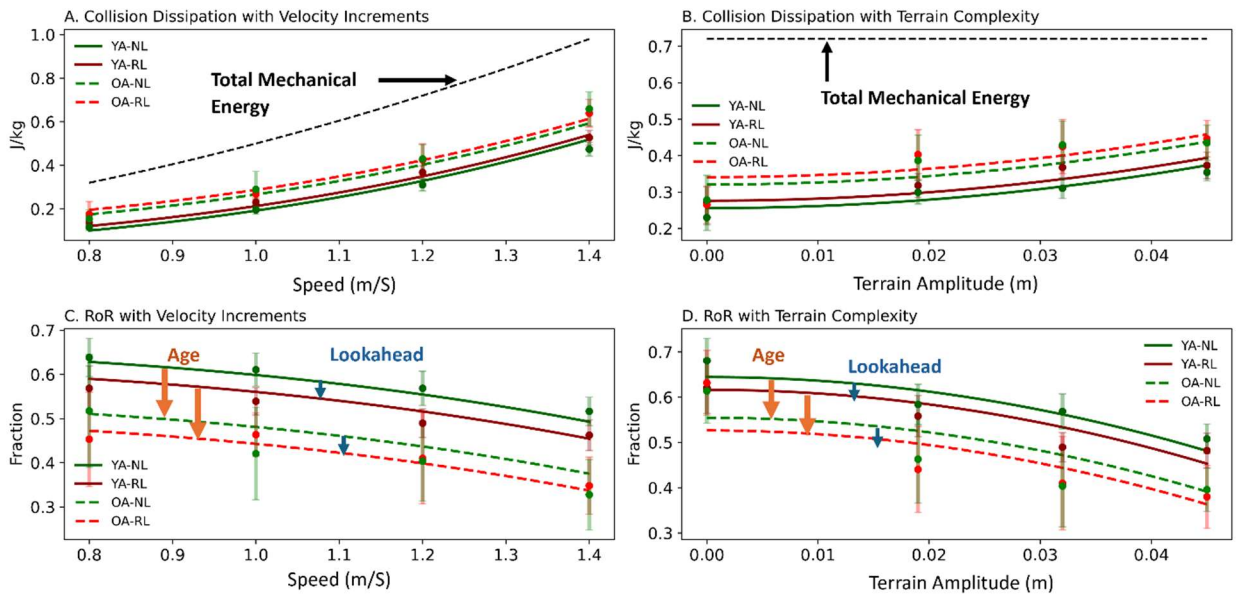

Figure 6: The calculated rate of recovery based on the experimental data and the modified definition: (A) the magnitude of the heel-strike collision energy waste with walking speed increase (Max_h = 0.032m). (B) the magnitude of the heel-strike collision energy dissipation with terrain amplitude rise (v = 1.2m/s). The normalized total mechanical energy trajectory is provided for reference (dashed line). (C) the rate of recovery trajectories for walking velocity increase, and (D) the rate of recovery trajectories for terrain amplitude rise. YA: young adults, OA: older adults, NL: normal lookahead, and RL: restricted lookahead.

Table 2: The statistical results summary for the heel strike collision dissipation work and the associated rate of recovery. The significant parameters are indicated by asterisk (*). The collision mechanical energy waste is defined as a negative value, as such, any positive gain indicates a decline in the magnitude of collision whereas a negative gain indicates an increase. The young adults' average (collision and rate of recovery) with normal lookahead for walking on a constant terrain amplitude (Max_h = 0.032 m) at different velocities are provided for reference.

	Average Collision Work					Rate of Recovery			
	Gains	P_values	Vels (m/S)	YA_W (J/kg)		Gains	P_values	Vels (m/S)	YA_W (J/kg)
Intercept*	0.1104	6.39E-08	0.8	-0.10	**Intercept***	0.72	2.05E-119	0.8	0.64
Vision*	0.0216	2.23E-03	1	-0.15	**Vision***	0.03	1.41E-03	1	0.61
Age	0.0346	2.24E-01	1.2	-0.20	**Age**	-0.07	9.86E-02	1.2	0.57
Velocity*	-0.2940	2.57E-112	1.4	-0.38	**Velocity***	-0.08	9.21E-07	1.4	0.52
Velocity-Age*	-0.0505	6.26E-03			**Age-Velocity**	-0.01	7.36E-01		
Max_h*	-54.1978	1.92E-10			**Max_h***	-70.85	5.53E-11		
Max_h-Age*	-21.8911	6.90E-02			**Age-Max_h***	-31.53	3.91E-02		

With the normal lookahead, the rate of recovery slightly increased by 0.03. However, there were no significant changes observed with age or the interaction of age and walking speed. On the other hand,

with velocity, the rate of recovery declined at a rate of -0.08 v^{-2}. Similarly, with terrain amplitude, the reduction rate was at -70.85 m^{-2}. With the interaction of age and terrain amplitude, we observed a higher variation rate (additional rate increase = -31.53 m^{-2}: 44.5%, Table 3).

Table 3: The rates of recovery ranges with walking velocity and terrain amplitude variations, for young and older adults with normal (NL) and restricted lookahead (RL). The changes are provided as percentages. With walking velocity or terrain amplitude increases, the rates of recovery declined.

Experimental Rate of Recovery

		Velocity Increments			Terrain Amplitude Increase		
				Change (%)			Change (%)
Young adults	**NL**	0.628	0.493	-21.50	0.644	0.481	-25.31
Young adults	**RL**	0.590	0.454	-23.05	0.616	0.453	-26.46
Older Adults	**NL**	0.511	0.375	-26.61	0.555	0.391	-29.55
Older Adults	**RL**	0.472	0.337	-28.60	0.526	0.363	-30.99

Discussion:

In this study, we aimed to propose a modified definition for the rate of recovery. This metric reflects the proportion of the previous step's total energy that is transferred to the subsequent step. Any energy difference that is dissipated during this transition is compensated for by the active work exerted on the COM at the onset of the next step. Our proposed definition of the rate of recovery, based on the COM work during the step-to-step transition, suggests that energy dissipation occurs not because of a failure in the conversion between potential and kinetic energy [4]. Rather, it is attributed to negative work performed during the heel strike [8, 10, 14], as it is assumed that at the point of transition, human walking significantly deviates from the motion of an inverted pendulum [14, 15].

Contrary to the previous version, which implied that there's a maximum rate of recovery associated with a specific velocity [4], the new definition suggests that as walking velocity increases, the rate of recovery continuously diminishes. This is because the collision impulse is directly proportional to walking velocity ($co \sim v_{ave}$) [14], resulting in increased energy waste with the square of walking velocity ($CO \sim v_{ave}^2$). Moreover, the new definition allows for predictions based on walking velocity. Specifically, it predicts that complete energy recovery occurs when walking velocity and step length are both zero. In essence, this implies that humans' legs must be planted on the ground, to force COM motion only resembles of an

inverted pendulum, to achieve perfect conservation of energy. Consequently, this approach cannot predict human preferred walking speeds.

Furthermore, in contrast to the older version, the updated method demonstrates significantly higher analytical rates of recovery when optimal push-offs are executed (ROR > 80%). This suggests that with pre-emptive push-offs, within the range of walking speeds, most of the energy from the previous step is transferred to the new step. It is proposed that the redirection of COM velocity by the pre-emptive push-off limits the magnitude of subsequent collision energy waste [1].

If the push-off is sub-optimal, the full energy required for forward progression is not induced preemptively. Consequently, the remaining necessary active mechanical work must be exerted after the transition. This post-transition active work may be partially or entirely performed by the torque at the hip joint [14], represented by active rebound work [8], or by the delayed push-off [6]. In contrast to optimal push-off exertion, where push-off and dissipation are balanced, the magnitude of energy waste increases significantly with reduced pre-emptive push-off. The adjusted rate of recovery suggests that such an approach is mechanically costly, as the rate of recovery is nearly halved when all active work is exerted after the heel-strike.

The experimental rates of recovery are notably higher than those predicted by the previous method [4], yet they remain materially lower than the analytical values. This suggests that the actual collision energy dissipation during human walking is greater than what the model proposes [13]. Hence, it is likely that there are additional dissipations in human walking beyond just the step-to-step collision impulses necessary for adjusting the COM velocity for the subsequent step [1]. It is plausible that a portion of the dissipation during heel-strike may be attributed to energy loss in soft tissue motion [25].

It is suggested that humans utilize visual information about the walking terrain to choose the next appropriate foothold [19]. Additionally, besides enhancing security and maintaining balance [2], it is proposed that selecting the proper foothold enables maximum conversion of potential to kinetic energy,

thereby reducing the required inducement of active work for the subsequent step [17, 18]. The reduction of heel-strike collisions with normal lookahead may also indicate that, in addition to the pre-emptive push-off, proper foot placement can limit the collision during heel-strike. While this effect may be small, it significantly increases the rate of recovery.

The reported higher metabolic rates observed in older adults' walking [7] may be linked to various factors, including age-related changes in muscle attributes [3, 24] and alterations in walking patterns [21]. The analytical simulation lacks the capability to differentiate between the rates of recovery in young and older adults since there is currently no mechanistic model to describe walking in older adults. However, the higher collision work and subsequent lower rates of recovery observed in older adults' walking may indicate that there are additional factors, beyond heel-strike, contributing to collision dissipation in this group. Further research is needed to fully elucidate these factors and their impact on walking biomechanics in older adults.

Overall, human walking during the single support phase may resemble the motion of an inverted pendulum [4, 16], but during the double support phase, the deviation in COM motion is considerable. Consequently, humans incur significant mechanical costs when transitioning from one stance leg to the next [9]. The modified rate of recovery, which is based on the step-to-step transition, demonstrates higher recovery rates when pre-emptive push-offs are utilized. This suggests that deviating from the preferred method of energizing the gait would be both mechanically and metabolically expensive. Despite showing similar declining trends, the experimental rates of recovery are lower than analytical estimates. This difference may be attributed to other dissipations such as mechanical energy waste in soft tissues during walking. Additionally, with restricted lookahead, uneven walking, and aging, the rates of recovery further decrease. This indicates that with these parameters, the dissipation during heel-strike also increases, resulting in higher energetic costs.

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Appendix 1:

In this section we outline the steps to define the modified rate of recovery (ROR) based on the analytical magnitude of the collision work as follows:

$$ROR = \frac{\frac{1}{2}v_{ave}^2 - CO}{\frac{1}{2}v_{ave}^2}$$

The collision impulse (Figure *1* – D) is calculated as:

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

Based on the collision impulse, the magnitude of the collision work dissipation is calculated:

$$co = v_{ave} \cdot \frac{\sin(2\alpha - \gamma)}{\cos\gamma} \rightarrow CO = \frac{1}{2}v_{ave}^2 \cdot (\frac{\sin(2\alpha - \gamma)}{\cos\gamma})^2$$

Having $\sin(2\alpha - \gamma) = \sin 2\alpha \cdot \cos\gamma - \cos 2\alpha \cdot sin\gamma$:

$$\frac{\sin(2\alpha - \gamma)}{\cos\gamma} = \frac{\sin 2\alpha \cdot \cos\gamma}{\cos\gamma} - \frac{\cos 2\alpha \cdot sin\gamma}{\cos\gamma} = \sin 2\alpha - \cos 2\alpha \cdot \tan\gamma$$

Having po impulse as $po_{rand} = v_{ave} \cdot \tan\ \gamma \rightarrow \tan\gamma = \frac{po_{rand}}{v_{ave}}$, therefore:

$$ROR = 1 - (\sin 2\alpha - \frac{po_{rand}}{v_{ave}} \cdot \cos 2\alpha)^2$$