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Braking and propulsive impulses increase with speed during accelerated and decelerated walking

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ABSTRACT

The ability to accelerate and decelerate is important for daily activities and likely more demanding than maintaining a steady-state walking speed. Walking speed is modulated by anterior–posterior (AP) ground reaction force (GRF) impulses. The purpose of this study was to investigate AP impulses across a wide range of speeds during accelerated and decelerated walking. Kinematic and GRF data were collected from 10 healthy subjects walking on an instrumented treadmill. Subjects completed trials at steady-state speeds and at four rates of acceleration and deceleration across a speed range of 0–1.8 m/s. Mixed regression models were generated to predict AP impulses, step length and frequency from speed, and joint moment impulses from AP impulses during non-steady-state walking. Braking and propulsive impulses were positively related to speed. The braking impulse had a greater relationship with speed than the propulsive impulse, suggesting that subjects modulate the braking impulse more than the propulsive impulse to change speed. Hip and knee extensor, and ankle plantarflexor moment impulses were positively related to the braking impulse, and knee flexor and ankle plantarflexor moment impulses were positively related to the propulsive impulse. Step length and frequency increased with speed and were near the subjects' preferred combination at steady-state speeds, at which metabolic cost is minimized in nondisabled walking. Thus, these variables may be modulated to minimize metabolic cost while accelerating and decelerating. The outcomes of this work provide the foundation to investigate motor coordination in pathological subjects in response to the increased task demands of non-steady-state walking.

1. Introduction

Daily living activities are mainly comprised of short duration walking bouts. Approximately 40% of all walking bouts for nondisabled adult individuals in typical urban environments consist of less than twelve consecutive steps [1]. Thus, the ability to accelerate and decelerate is important for daily activities and likely more demanding than maintaining a steady-state speed. Walking speed is regulated by anterior–posterior ground reaction force (AP GRF) impulses. Few studies have investigated AP GRFs during accelerated and decelerated walking and were conducted at very fast walking speeds near the walk-to-run transition speed [2–5]. Only one study was conducted across moderate walking speeds to examine acceleration and deceleration and found that walking speed was altered in early stance by reducing (during acceleration) or increasing (during deceleration) the braking impulse (i.e., time integral of the negative AP GRF) [6]. However, only a small speed increase and decrease (1.0–1.4 m/s) could be investigated due to the subjects walking overground across two force plates.

As a result, current insights into how healthy subjects accelerate and decelerate are primarily inferred from comparisons across steady-state speeds. Step length and frequency influence AP impulses and increase with increasing steady-state speeds [7]. Increases in peak AP GRFs and AP impulses occur with increasing step length when walking at a steady-state speed [8]. Increasing step frequency during steady-state walking presumably decreases the AP impulse (i.e., the AP GRF is integrated over a shorter time). Nilsson and Thorstensson [9] found braking and propulsive (i.e., positive AP impulse) impulses increased with steady-state speeds from 1.0 to 2.0 m/s, but braking and propulsive impulses decreased with speed from 2.0 to 3.0 m/s. Thus, as steady-state speed increased from 1.0 to 2.0 m/s, step length may have influenced AP impulses more than step frequency, whereas step frequency may have influenced AP impulses more than step length from 2.0 to

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3.0 m/s, possibly because subjects could not further increase their step length at walking speeds faster than the walk-to-run transition. During acceleration and deceleration across moderate walking speeds where saturation of step length is not likely to occur, it remains unclear how step length and frequency will influence the AP impulses.

Identifying relationships between joint moments and braking and propulsive impulses would provide further insight into mechanisms of accelerated and decelerated walking. At self-selected speeds, simulation analyses have shown the ankle plantarflexor moment is the largest contributor to AP acceleration [10]. Other simulation analyses have quantified individual muscle contributions to AP acceleration at self-selected speeds [11,12] and across steady-state speeds [13,14]. Neptune et al. [11,13] quantified AP acceleration of the trunk and Liu et al. [12,14] quantified AP acceleration of the body center-of-mass. In agreement, these studies found that the hip extensors and vasti group are the main contributors to AP deceleration in early stance and soleus and gastrocnemius are the main contributors to AP acceleration in late stance. Furthermore, these contributions increased with walking speed. Neptune et al. [15] also found that SOL and GAS each contribute to AP deceleration in mid-stance, though Liu et al. [12] did not. However, Liu et al. [12] found that if they excited SOL during mid-stance, in agreement with previous EMG studies [16,17], SOL does indeed contribute to AP deceleration.

The primary purpose of this study was to identify the relationships between walking speed and AP impulses, step length and step frequency in healthy subjects accelerating and decelerating at different rates across a speed range of 0.4 to 1.8 m/s. The hypothesis that braking and propulsive impulses, step length and step frequency would increase with speed during non-steady-state walking was tested. In addition, relationships between AP impulses and joint moment impulses were analyzed and the hypotheses that the ankle plantarflexor moment impulse would positively relate to braking and propulsive impulses and that the hip and knee extensor moment impulses would positively relate to the braking impulse during non-steady-state walking were tested.

2. Methods

Kinematic and GRF data were collected from 10 healthy subjects (five females, five males; age = 28.7 ± 5.8 yrs, mass = 69.6 ± 13 kg, height = 1.73 ± 0.12 m, leg length = 0.827 ± 0.055 m) during treadmill walking at the VA Brain Rehabilitation Research Center in Gainesville, FL. All participants signed a written informed consent and the Institutional Review Board approved the protocol. Reflective markers were placed on the head (top, left and right temple, and back), trunk (C7, T10, clavicle, sternum and right scapula), and arms (left and right shoulder, elbow and wrist). Clusters of reflective markers were attached to the pelvis and left and right thigh, shank, and foot segments. Marker trajectories were recorded at 100 Hz with a 12-camera motion capture system (Vicon, Oxford, UK) and GRF data were measured at 2000 Hz as subjects walked on a split-belt instrumented treadmill (Bertec Corporation, Columbus, OH). All data were collected using Vicon Workstation v4.5 software (Vicon, Oxford, UK). A safety harness that did not provide body weight support was worn during all trials to protect subjects in case of a loss of balance.

Following a static calibration trial, each subject completed a 30 s walking trial at their self-selected speed, followed by 30 s walking trials at steady-state speeds of 0.4, 0.8, 1.2, 1.6 and 1.8 m/s in random order. These steady-state data were collected to compare with steps at similar instantaneous speeds during non-steady-state walking. Subjects then completed randomized blocks of acceleration and deceleration trials at rates of 0.03, 0.06, 0.09 and 0.12 m/s^2. Data were collected during three trials at each rate as subjects accelerated from 0 to 1.8 m/s, maintained a speed of 1.8 m/s for approximately 10 s (data were not collected during this time), and then decelerated from 1.8 to 0 m/s. Data at different rates were collected to provide a framework for investigating acceleration and deceleration in patient populations (e.g., post-stroke hemiparetic patients) that likely accelerate and decelerate at decreased rates compared to nondisabled walkers.

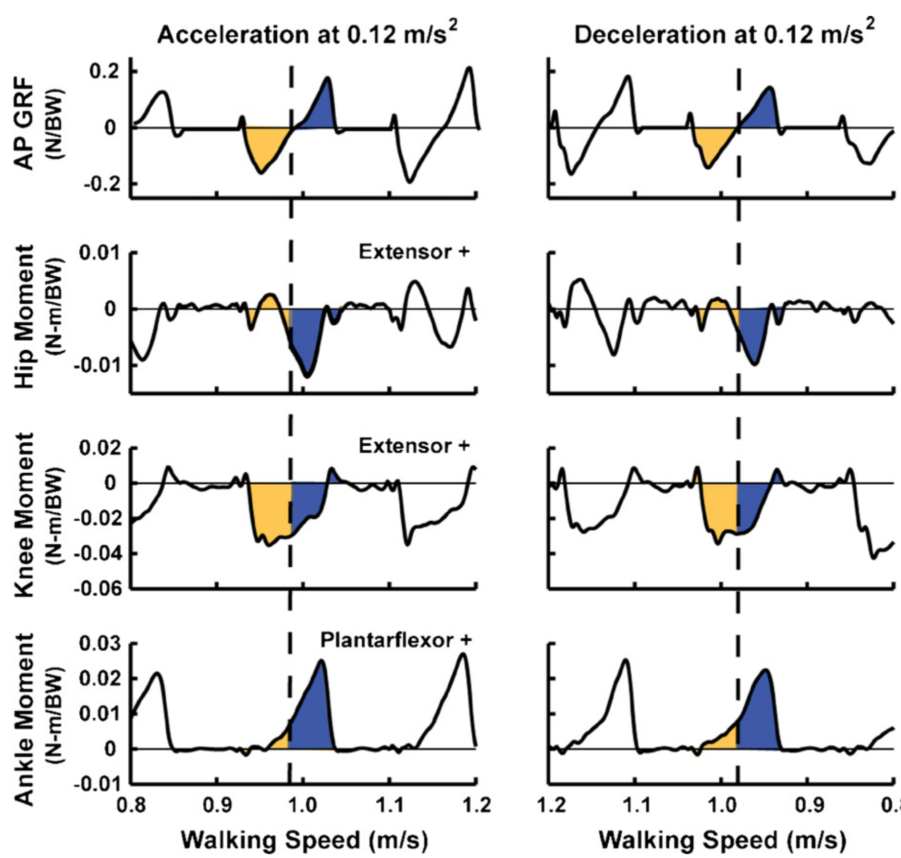

Fig. 1. Hip, knee and ankle moment impulses were computed for each step during the braking (yellow) and propulsive (blue) phases in order to identify relationships between joint moment impulses with the braking and propulsive impulses, respectively. Anterior–posterior ground reaction forces (AP GRFs) and joint moments were normalized by subject body weight (BW). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

All data were time synchronized and processed using Visual3D (C-motion, Inc., Germantown, MD) and analyzed within the speed range of 0.4 to 1.8 m/s using MATLAB (The Mathworks, Inc., Natick, MA). Kinematic and GRF data were low pass filtered with a fourth order Butterworth filter with cutoff frequencies of 6 and 20 Hz, respectively. A standard inverse dynamics analysis was performed to determine the intersegmental joint moments using Visual3D. Kinetic data (GRFs and joint moments) were normalized by each subject's body weight (see Supplementary data for representative trials at each rate of acceleration and deceleration). Step length and step frequency were determined for each step from heel marker trajectories and GRF data. Step lengths were normalized by each subject's leg length, which was computed as the vertical distance from the greater trochanter to the ankle joint center during the static calibration trial. Braking and propulsive impulses and flexor and extensor joint moment impulses (i.e., time integral of the flexor and extensor joint moment trajectories, respectively) for the hip, knee and ankle joints were computed for each step during the braking and propulsive phases (Fig. 1). The absolute values of negative impulses (i.e., braking, hip and knee flexor moment, and ankle dorsiflexor moment) were computed.

Linear mixed regression models were generated using SPSS 16.0 GP Statistical Software (SPSS Inc., Chicago, IL) to determine relationships between walking speed and braking impulse, propulsive impulse, step length and step frequency during non-steady-state walking. In addition, linear mixed models were generated to determine relationships between braking and propulsive impulses each with hip, knee and ankle moment impulses during the braking and propulsive phases, respectively. Each model was generated with rate of acceleration or deceleration as a fixed factor and the intercept (i.e., value of the dependent variable when walking speed is 0 m/s) as a random effect. Models were generated to predict the dependent variable (Y) (Eq. (1)) where coefficient^{Main} represents the main effect of the independent variable (X) on Y, and coefficient^{Rate} represents the combined effect of rate and X. For example, a model to predict the braking impulse (Y) was generated where intercept^{Main} and coefficient^{Main} account for the main effect of walking speed (X) on the braking impulse, and intercept^{Rate} and coefficient^{Rate} account for differences in the prediction of braking impulse due to rate. Significance of model coefficients was set at $p < 0.05$. Significance of intercepts (values at 0 m/s) was not analyzed because a linear model was inappropriate for walking speeds less than 0.4 m/s and only model predictions between speeds of 0.4 and 1.8 m/s were of interest.

$$Y = (\text{Intercept}^{\text{Main}} + \text{Intercept}^{\text{Rate}}) + (\text{Coefficient}^{\text{Main}} + \text{Coefficient}^{\text{Rate}})X \quad (1)$$

3. Results

The braking impulse was positively related to speed (i.e., the braking impulse became more negative as walking speed increased) during non-steady-state walking (Table 1, coefficient = 0.0099, $p < 0.001$). Compared to the braking impulse while subjects decelerated at the highest rate (i.e., -0.12 m/s^2), braking impulses at acceleration rates of 0.06, 0.09 and 0.12 m/s^2 and deceleration at rates of 0.06 and 0.09 m/s^2 had greater positive coefficients with walking speed (Table 1). Propulsive impulses were positively related to speed (Table 1, coefficient = 0.0042, $p < 0.001$). Compared to the propulsive impulse while subjects decelerated at 0.12 m/s^2, the propulsive impulse during acceleration and deceleration at rates of 0.03, 0.06 and 0.09 m/s^2 had greater positive coefficients with walking speed (Table 1). Average braking and propulsive impulses generated during steady-state walking trials were predicted by the model at each rate of acceleration or deceleration (Fig. 2, data shown for a representative subject).

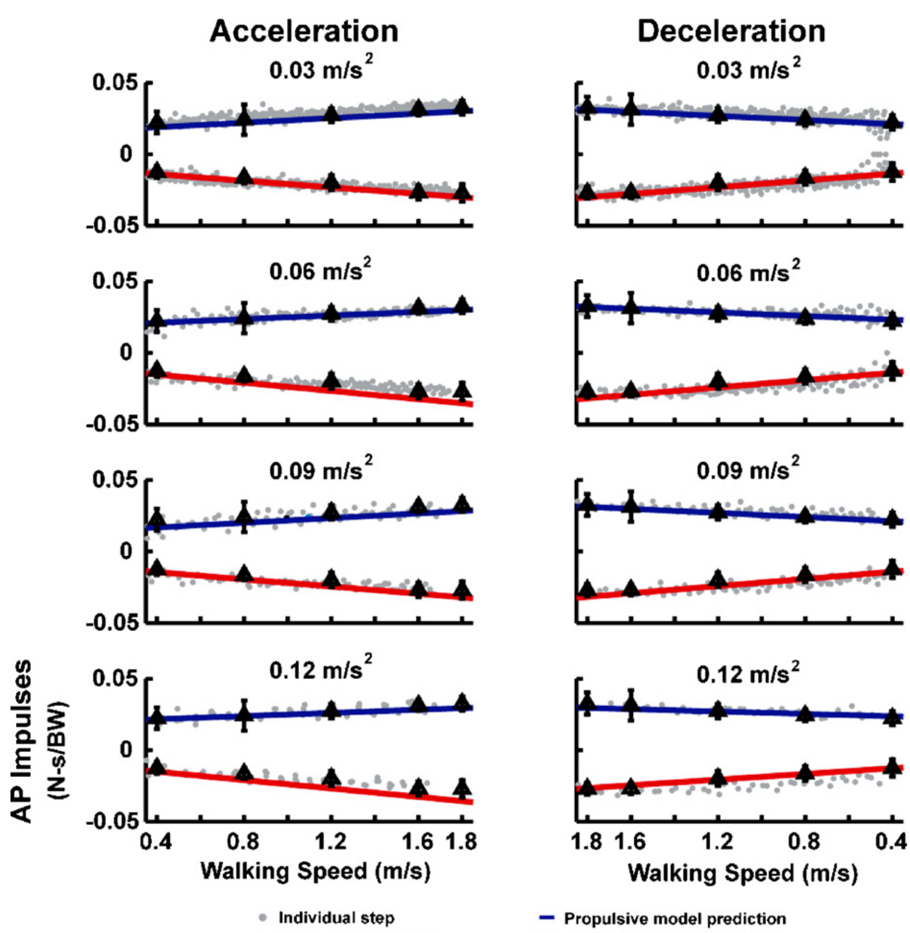

Fig. 2. Anterior–posterior (AP) ground reaction force impulses increased with walking speed during accelerated and decelerated walking. The braking impulse (shown as negative although the absolute value was used for regression analyses) had a greater relationship with walking speed than the propulsive impulse at each rate. Linear mixed regression models were generated from data collected from 10 subjects and are compared to individual steps from three trials for a representative subject at each rate and their mean AP impulses (error bars are ±3 standard deviations) at steady-state speeds.

Table 1
Linear mixed regression model coefficients (Coeff.) and intercepts (Int.) to predict braking impulses, propulsive impulses, step length and step frequency from walking speed during accelerated and decelerated walking. Model coefficients for the main effect of walking speed are shown in the top row. Interaction effects due to rate were determined with respect to deceleration at 0.12 m/s^2 for ease of comparison to other conditions, although any rate could have served as the reference. As an example, the main effect of walking speed (WS) on the absolute value of the braking impulse at 0.06 m/s^2 is 0.0099 × WS, and the interaction due to rate is 0.0044 × WS. The absolute value of the braking impulse (BI) can be predicted from walking speed with the following equation: BI = (0.0099 + 0.0044) × WS. Significance of the model coefficients are indicated by *($p < 0.05$) and †($p < 0.001$).

	Braking impulse		Propulsive impulse		Step length		Step frequency	
	Coeff.	Int.	Coeff.	Int.	Coeff.	Int.	Coeff.	Int.
Speed	0.0099†	0.019	0.0042†	0.031	0.34†	0.44	0.73†	0.79
Rate (m/s^2)								
0.03	0.0016	−0.0034	0.0038†	−0.0055	−0.036†	0.038	0.070†	−0.041
0.06	0.0044†	−0.0074	0.0022*	−0.0027	0.0029	−0.0078	0.065†	−0.044
0.09	0.0027*	−0.0045	0.0040†	−0.0077	−0.024*	−0.0025	0.015	0.033
0.12	0.0038†	−0.0048	0.0014	−0.0018	0.014	−0.011	0.041*	−0.028
−0.03	0.0019	−0.0030	0.0030*	−0.0056	−0.017	−0.0050	0.011	0.034
−0.06	0.0029*	−0.0033	0.0022*	−0.0033	0.016	−0.018	0.024	0.0015
−0.09	0.0026*	−0.0033	0.0030*	−0.0055	−0.019	−0.0021	0.0016	0.048
−0.12	–	–	–	–	–	–	–	–

Step length was positively related to speed (Table 1, coefficient = 0.34, $p < 0.001$) and had smaller positive relationships for acceleration at rates of 0.03 and 0.09 m/s^2 compared to deceleration at 0.12 m/s^2 (Table 1). Step frequency was positively related to speed (Table 1, coefficient = 0.73, $p < 0.001$) and had greater positive relationships for acceleration at rates of 0.03, 0.09 and 0.12 m/s^2 compared to deceleration at 0.12 m/s^2 (Table 1). Average step lengths and frequencies during steady-state trials were predicted by the model for accelerated and decelerated walking, with only a few exceptions for some subjects (Fig. 3, data shown for a representative subject).

The hip extensor moment impulse during the braking phase was positively related to the braking impulse (i.e., the braking impulse became more negative as the hip extensor moment increased) during non-steady-state walking (Table 2, coefficient = 0.064, $p < 0.001$). The knee extensor moment impulse was positively related to the braking impulse (Table 2, coefficient = 0.12, $p = 0.004$). The ankle plantarflexor and dorsiflexor moment impulses were

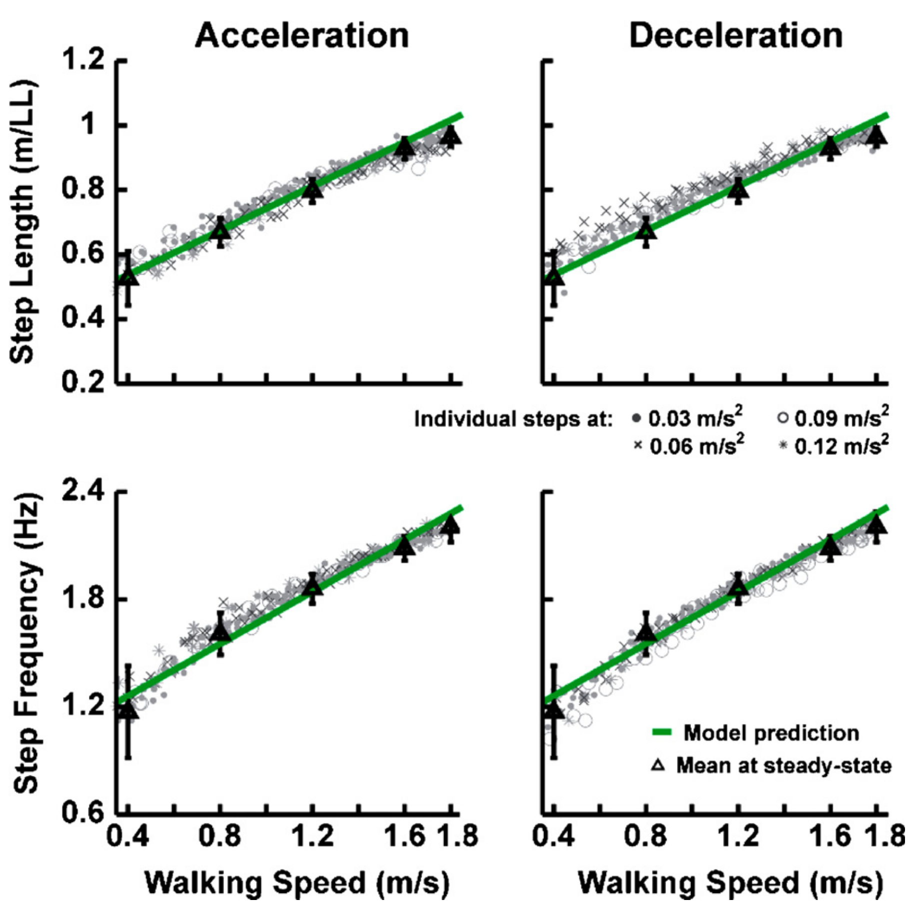

Fig. 3. Step length (normalized by leg length (LL)) and frequency increased with walking speed during accelerated and decelerated walking. Linear mixed models generated from data across 10 subjects well predicted mean step lengths and frequencies (error bars are ±3 standard deviations) by a representative subject at steady-state speeds compared with individual steps during three trials at each rate.

Table 2
Linear mixed model coefficients and intercepts (Int.) to predict braking and propulsive impulses from joint moment impulses generated during accelerated and decelerated walking. Significance of the model coefficients are indicated by *($p < 0.05$) and †($p < 0.001$).

	Braking impulse		Propulsive impulse	
	Coefficient	Int.	Coefficient	Int.
Hip extensor impulse	0.24†	−0.028	−0.92	0.088
Hip flexor impulse	−0.25	0.022	0.033	0.0048
Knee extensor impulse	0.12*	0.00037	0.0015	0.0024
Knee flexor impulse	0.0076	0.0014	0.021†	−0.00006
Ankle plantarflexor impulse	0.12†	0.00077	0.14†	0.0043
Ankle dorsiflexor impulse	−0.047†	0.0027	−0.0035	−0.00096

positively and negatively related to the braking impulse, respectively (Table 2, plantarflexor coefficient = 0.12, $p < 0.001$; dorsiflexor coefficient = −0.047, $p < 0.001$). During the propulsive phase, the knee flexor moment impulse (Table 2, coefficient = 0.021, $p < 0.001$) and the ankle plantarflexor moment impulse were positively related to the propulsive impulse (Table 2, coefficient = 0.14, $p < 0.001$). Rate of acceleration or deceleration did not significantly change the relationships between braking and propulsive impulses with joint moment impulses.

4. Discussion

The primary purpose of this study was to identify relationships between walking speed and AP impulses, step length and step frequency during accelerated and decelerated walking on a treadmill. The hypothesis that braking and propulsive impulses would increase with speed from 0.4 to 1.8 m/s was supported (Fig. 2). This result is consistent with a previous study that found braking and propulsive impulses increase with increasing steady-state speeds from 1.0 to 2.0 m/s during overground walking [9]. Average braking and propulsive impulses were similar between steady-state trials and at the same speed during accelerated and decelerated walking, suggesting that these quantities at steady-state speeds may estimate their values in accelerated and decelerated walking. The hypothesis that step length and frequency would increase with walking speed during acceleration and deceleration was supported and is consistent with previous studies at steady-state speeds [7,18]. Subjects were able to modulate step length and frequency while accelerating and decelerating to attain step lengths and frequencies within three standard deviations of their average values during steady-state trials (Fig. 3). Over this range of moderate steady-state speeds, nondisabled walkers have been shown to choose step frequencies that minimize the rate of metabolic energy expenditure [19,20]. Therefore, these results suggest that subjects may also modulate step frequency to minimize metabolic cost while accelerating and decelerating.

The braking impulse had a greater positive relationship with walking speed than the propulsive impulse at each rate of acceleration and deceleration (Fig. 2), suggesting that subjects modulate their braking impulse more than the propulsive impulse to change speed. Similarly, Orendurff et al. [6] found that subjects accelerated and decelerated across a speed range of 1.0 to 1.4 m/s by either decreasing (during acceleration) or increasing (during deceleration) the early stance braking impulse, which was modulated by the ankle plantarflexor moment. In agreement with Orendurff et al. [6], the ankle plantarflexor moment was related to braking in the current study (i.e., the ankle plantarflexor and dorsiflexor moment impulses were positively and negatively related to the braking impulse, respectively). However, in the present study the hip and knee extensor moments were also positively related to braking. This finding supported the hypothesis that the hip and knee extensor moments would positively relate to the braking impulse and agreed with previous simulation analyses of steady-state walking over a range of speeds [13,14]. In contrast with Orendurff et al. [6], we found the propulsive and braking impulses increased (i.e., braking impulses became more negative) with speed during acceleration. Our finding that subjects increased braking more than the propulsive impulse during acceleration was due to longer gait cycle durations at slow compared to fast walking speeds. At slow walking speeds, a greater change in speed was accomplished over each gait cycle while gait cycle durations were longer compared to fast speeds. Thus, as walking speed increased during acceleration, gait cycle durations decreased and the change in speed accomplished over a gait cycle decreased. A decreased change in speed over a gait cycle was realized by increasing the braking impulse more than the propulsive impulse, although, the magnitude of the braking impulse remained less than the propulsive impulse throughout acceleration. The hypothesis that the ankle plantarflexor moment would positively relate to the propulsive impulse was supported, and is consistent with the functional role of the plantarflexors to provide forward propulsion [10,15,21]. Also, increased force by gastrocnemius to provide swing initiation as speed increased [13] may have contributed to the positive relationship between the knee flexor moment and propulsive impulse.

The rate of acceleration or deceleration did not have a strong effect on the relationships between braking and propulsive impulses with speed. Although differences existed due to rate, the range of the model coefficients was small. For example, model coefficients to predict the braking impulse from walking speed ranged only from 0.0099 (Table 1, -0.12 m/s^2) to 0.0143 (Table 1, 0.0099 + 0.0044 = 0.0143 at 0.06 m/s^2). Thus, at a walking speed of 1.0 m/s, the predicted braking impulses were 0.0289 and 0.0259 N m/BW at rates of -0.12 m/s^2 and 0.06 m/s^2, respectively. In addition, the effect of rate on the relationships between walking speed and step length and step frequency were not significant for most conditions, and was small for those conditions that were significant. Model coefficients to predict step length from walking speed ranged only from 0.34 during deceleration at 0.12 m/s^2 to 0.304 during acceleration at 0.03 m/s^2 (Table 1, 0.34 − 0.036 = 0.304). Similarly, model coefficients to predict step frequency from walking speed ranged only from 0.73 to 0.80. These results suggest that rate is not an important factor in modulating AP impulses, step length and step frequency during accelerated and decelerated walking.

An important delimitation of this study is that data were collected on a treadmill. The use of the instrumented treadmill allowed for speed to be controlled over a wide range of values during accelerated and decelerated walking, which is difficult to achieve overground. A recent study compared the AP impulse between overground and treadmill walking at steady-state speeds and found there is no fundamental difference in propulsion mechanics [22]. However, a non-inertial reference frame (e.g., the accelerating treadmill) exerts an inertial force on a subject due to the acceleration of the treadmill belt such that acceleration on a treadmill may be subtly different from overground. This inertial force, which is greater for higher rates of acceleration or deceleration, may have contributed to the small differences in the relationships between AP impulses and speed due to rate. The range of speeds studied and potential differences in accelerated and decelerated walking on a treadmill versus overground may account for the additional relationships reported in the current study that were not observed by Orendurff et al. [6]. Nonetheless, the strong similarity between AP impulses at steady-state (while no inertial forces exist) and at the same speed during accelerated and decelerated walking (while inertial forces exist) [22] suggests that the inertial forces are low and have little effect on AP impulses.

In conclusion, braking and propulsive impulses were positively related to walking speed during acceleration and deceleration on a treadmill. The braking impulse had a greater positive relationship with walking speed than the propulsive impulse, suggesting that subjects modulate the braking impulse more than the propulsive impulse to change speed. Hip and knee extensor, and ankle plantarflexor moment impulses were positively related to the braking impulse, and knee flexor and ankle plantarflexor moment impulses were positively related to the propulsive impulse. Step length and frequency increased with walking speed and were near subjects' preferred step length and frequency at steady-state speeds suggesting that these variables may be modulated to minimize metabolic cost during non-steady-state walking. The outcomes of this work provide the foundation to investigate motor coordination during acceleration and deceleration in pathological subjects who are likely limited in their ability to modulate AP impulses and minimize metabolic cost during non-steady-state walking.

Acknowledgements

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Conflict of interest

There is no conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2011.01.010.

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