

Leg extension is an important predictor of paretic leg propulsion in hemiparetic walking

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ABSTRACT

Forward propulsion is a central task of walking that depends on the generation of appropriate anterior–posterior ground reaction forces (AP GRFs). The AP impulse (i.e., time integral of the AP GRF) generated by the paretic leg relative to the non-paretic leg is a quantitative measure of the paretic leg's contribution to forward propulsion and is variable across hemiparetic subjects. The purpose of this study was to investigate the underlying mechanisms of propulsion generation in hemiparetic walking by identifying the biomechanical predictors of AP impulses.

Three-dimensional kinematics and GRFs were recorded from 51 hemiparetic and 21 age-matched control subjects walking at similar speeds on an instrumented treadmill. Hierarchical regression models were generated for each leg to predict the AP impulse from independent biomechanical variables.

Leg extension was a significant predictor and positively related to the propulsive impulse in the paretic, non-paretic and control legs. Secondly, the hip flexor moment impulse was negatively related to the propulsive impulse. Also, the relationship of paretic and non-paretic ankle moments with the propulsive impulse depended on the paretic step ratio, suggesting that the plantar flexor contribution to the propulsive impulse depends on leg angle. These results suggest that increasing paretic leg extension will increase propulsion. Increasing paretic plantar flexor output and decreasing paretic hip flexor output could also increase paretic leg propulsion. While increased pre-swing hip flexor output has been suggested to compensate for decreased plantar flexor output, such output may further impair propulsion by the paretic leg if it occurs too soon in the gait cycle.

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1. Introduction

Improved walking performance is an important goal for rehabilitation following stroke with walking speed being a widely used measure of recovery [1] and surrogate for functional walking ability [2]. However, because increased speed can be achieved via a greater use of the non-paretic leg as a compensatory mechanism, walking speed alone may not effectively identify paretic leg motor control impairments [3]. Forward propulsion of the body center of mass (COM) is a central task of walking that depends on the generation of appropriate anterior–posterior ground reaction forces (AP GRFs). Thus, a measure based on the paretic leg's contribution to the AP GRF may be more effective than walking speed at distinguishing functional compensation by the non-

paretic leg from the restitution of neurological deficits in the paretic leg.

Subjects with hemiparesis typically walk with asymmetric AP GRFs such that the propulsive impulse (i.e. time integral of the positive AP GRF) generated by the paretic and non-paretic legs are not equal [3]. Also, they generate a wide range of paretic propulsion (P_p = paretic propulsive impulse/total propulsive impulse generated by both legs). Generally, most subjects generate less propulsion in the paretic leg compared to the non-paretic leg. However, some subjects who walk at slower speeds consistently exhibit more paretic leg propulsion [4]. Understanding mechanisms of propulsion generation within individual subjects would allow for the design of subject-specific rehabilitation strategies and potentially improve intervention outcomes.

Several factors that affect AP GRF impulse production by hemiparetic subjects have been proposed such as the inability to recruit muscles responsible for generation of propulsion, increased activity in muscles that impair generation of propulsion, and indirect mechanics related to step length. The primary contributors to the

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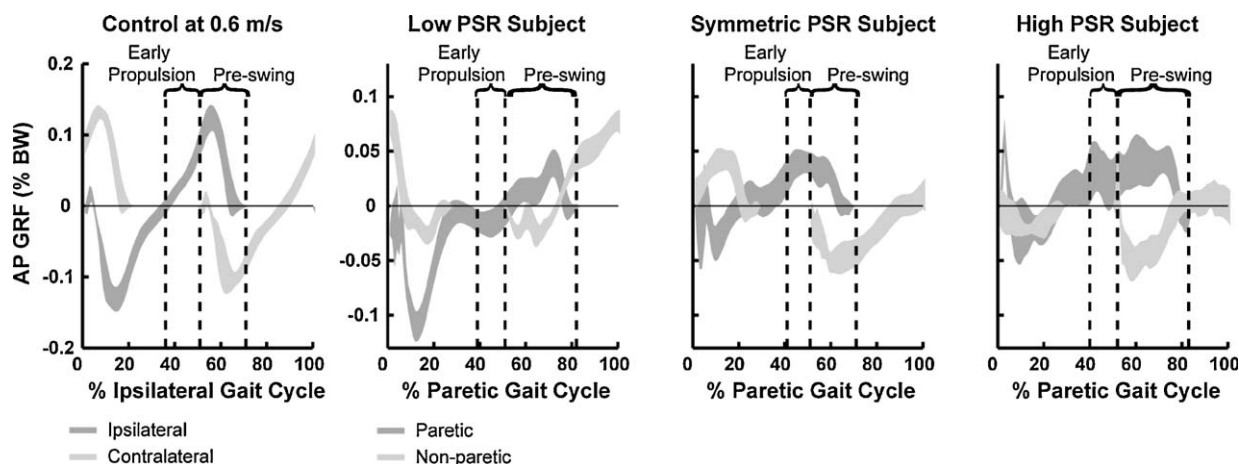


Fig. 1. The propulsive phase was divided into early propulsion (i.e., second 50% of single leg stance) and pre-swing (i.e., second double support phase) from anterior–posterior ground reaction force (AP GRF) records and are shown for a control subject walking at 0.6 m/s and a representative subject with hemiparesis from each paretic step ratio (PSR = paretic step length/(non-paretic + paretic step length)) subgroup. Average paretic (ipsilateral for control) and non-paretic (contralateral for control) leg AP GRFs are shown with ± 1 standard deviation of the 30 s walking trial and are normalized to the paretic (ipsilateral for control) leg gait cycle. Early propulsion and pre-swing regions and biomechanical variables within each region were determined for individual gait cycles for each leg.

propulsive impulse in healthy walking adults are the ankle plantar flexors [5–7]. An overground study of hemiparetic walking found that the paretic propulsive impulse positively correlated with gastrocnemius and soleus muscle activity in late stance and pre-swing [8], which was consistent with other studies suggesting that plantar flexor activity is important for attaining faster walking speeds in hemiparetic gait [9,10]. Thus, impairments affecting the output from these muscles (e.g., muscle paresis, spasticity, increased antagonist coactivation, increased passive stiffness) would be expected to affect AP GRF impulses.

Recent studies of hemiparetic walking reported negative relationships between self-selected walking speed and step length asymmetry [11], and negative relationships between Pp and step length asymmetry [4], which suggests that indirect mechanics related to step length may also affect AP GRF impulses. Because extensor muscle force generation in the leg accelerates the body when the foot is posterior to the body COM, decreased paretic propulsion may be attributed to decreased paretic leg extension (i.e., leg orientation with respect to vertical) in late stance commonly observed in the paretic leg [12,13].

Another mechanism affecting the AP GRF impulses may be exaggerated flexor activity that counteracts appropriate plantar flexor output by prematurely offloading the leg and interfering with the leg's ability to generate propulsion. For example, compensation by the paretic hip flexors during late stance to advance the leg further anterior at heel strike may limit the posterior position of the paretic foot at push-off [12]. Indeed, negative correlations between the paretic propulsive impulse and paretic rectus femoris and tibialis anterior activity during late stance in subjects with severe hemiparesis have been reported during overground walking [8].

The primary goal of this study was to investigate the underlying mechanisms of propulsion generation during hemiparetic walking by identifying predictors of the AP GRF impulses from mid to late stance. We hypothesized that the paretic plantar flexor moment impulse (i.e., time integral of the moment), leg extension angle, and hip flexor moment impulse are important predictors of the paretic AP GRF impulse from mid to late stance with positive, positive and negative relationships, respectively.

2. Methods

2.1. Subjects

Fifty-one subjects with chronic hemiparesis (32 left hemiparesis, 32 men, 19 women; age 62.4 ± 12.0 years; 8.8 ± 5.1 years post-stroke) and 21 age-matched

healthy subjects (4 men, 17 women; age 65.2 ± 9.6 years) were recruited at the VA Brain Rehabilitation Research Center. Inclusion criteria for the hemiparetic subjects were hemiparesis secondary to a single unilateral stroke, free of significant lower extremity joint pain and major sensory deficits, able to ambulate independently without an assistive device over 10 m on a level surface, walk on a daily basis in the home, no significant lower limb contractures, and no significant cardiovascular impairments contraindicated to walking. Subjects were excluded from the study if they had any orthopedic or neurologic (i.e., in addition to that caused by stroke) conditions. All subjects signed informed consent and Institutional Review Boards of the University of Florida and The University of Texas at Austin approved the protocol.

2.2. Experimental set-up and procedure

Subjects completed three 30 s walking trials on an instrumented split-belt treadmill (Tecmachine¹) at their self-selected (SS) treadmill walking speed without use of an assistive device or ankle-foot orthosis. Control subjects completed additional trials at 0.3, 0.6 and 0.9 m/s to provide speed-matched comparisons with the hemiparetic subjects. Bilateral 3D GRFs were recorded at 2000 Hz and kinematic data were recorded using a twelve-camera motion analysis system (Vicon Motion Systems²) at 100 Hz after the subjects had reached steady-state walking. A modified Helen Hayes marker set was used to define each body segment with additional marker triads attached to rigid plates located on each foot, shank and thigh segment.

2.3. Data analysis

Hemiparetic walking data at SS speed (0.41 ± 0.25 m/s) and corresponding control data at SS speed (0.93 ± 0.27 m/s), 0.3 and 0.6 m/s were processed using Visual 3D³. Raw kinematic and GRF data were low-pass filtered using a fourth-order zero-lag Butterworth filter with cutoff frequencies of 6 and 20 Hz, respectively. Standard inverse dynamics analysis determined intersegmental joint moments. All data were time normalized to 100% of each leg's gait cycle. Kinetic data were normalized by subject body weight. Leg angle was computed as the angle between a line from the pelvis COM to the foot COM and vertical (positive when foot is posterior to the pelvis).

The ipsilateral stance phase was subdivided into the typical braking and propulsive phases of the unimpaired stance phase that account for temporal abnormalities of the paretic gait cycle [14]. The propulsive phase was further divided into two regions defined by the GRF records: early propulsion (i.e., second 50% of single leg stance) and pre-swing (i.e., second double support phase) (Fig. 1). Gait variables calculated within each region for each gait cycle included the AP impulse, average leg angle and hip (flexor positive), knee (extensor positive) and ankle (plantar flexor positive) moment impulses.

2.4. Statistical analysis

Regression analyses were performed with two-level hierarchical models for the control group at speeds of 0.3, 0.6 m/s and SS, and for the hemiparetic group at SS speed in each region to examine relationships between the AP impulse with biomechanical variables, while accounting for correlations due to repeated measures

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³ C-Motion, Inc., 20030 Century Blvd, Suite 104, Germantown, MD 20874.

Table 1

Averages (Avg.) and standard deviations (S.D.) of paretic, non-paretic and control leg (average of left and right legs) variables during early propulsion and pre-swing across hemiparetic subgroups walking at self-selected (SS) speeds and control subjects walking at 0.3, 0.6 m/s and SS speed. Hemiparetic subgroups were determined by the paretic step ratio (PSR) (low: PSR < 0.47; symmetric: $0.47 \leq \text{PSR} \leq 0.53$; high: PSR > 0.53).

	Hemiparetic Subgroups						Controls					
	N = 9 Low PSR		N = 16 Symm.		N = 26 High PSR		N = 21 0.3 m/s		N = 21 0.6 m/s		SS	
SS treadmill speed (m/s)	0.49	0.3	0.57	0.2	0.28	0.2					0.93	0.3
Early Propulsion							Avg.		S.D.			
Paretic Leg												
AP impulse (N-s)	5.7	3	3.0	2	0.245	4	2.8	3	3.9	3	6.9	4
Average leg angle (deg)	8.1	4	7.5	3	2.13	4	5.6	2	7.9	2	10.7	2
Hip moment impulse (N-m-s)	2.5	37	28.5	28	-5.49	39	-0.9	60	0.7	62	11.6	54
Knee moment impulse (N-m-s)	-35.9	35	-3.3	44	-22.1	55	-13.5	53	-22.7	50	-31.6	38
Ankle moment impulse (N-m-s)	130.2	64	125.0	64	70.1	57	147.0	69	165.0	63	171.0	46
Non-paretic Leg												
AP impulse (N-s)	0.4	4	5.1	4	5.4	6						
Average leg angle (deg)	5.6	3	8.2	3	7.1	3						
Hip moment impulse (N-m-s)	12.4	36	50.2	60	29.1	62						
Knee moment impulse (N-m-s)	-8.9	37	-16.3	44	10.1	59						
Ankle moment impulse (N-m-s)	154.0	79	192.0	69	192.0	82						
Pre-swing												
Paretic Leg												
Ipsilateral AP impulse (N-s)	7.5	6	4.6	5	-3.5	6	10.4	5	13.8	4	16.4	4
Contralateral AP impulse (N-s)	-4.8	3	-1.8	5	3.5	5	-3.4	3	-6.7	3	-9.9	4
Average leg angle (deg)	16.2	6	16.0	4	7.6	6	12.9	3	17.6	2	23.0	3
Hip moment impulse (N-m-s)	39.8	32	89.4	51	45.3	64	35.1	71	39.4	52	54.1	37
Knee moment impulse (N-m-s)	-24.1	47	24.0	51	-25.5	70	-12.4	54	-6.2	35	3.1	20
Ankle moment impulse (N-m-s)	163.0	60	165.0	70	140.0	82	247.0	95	192.0	57	138.0	37
Non-paretic Leg												
Ipsilateral AP impulse (N-s)	6.3	5	12.5	6	11.9	7						
Contralateral AP impulse (N-s)	-0.1	3	-2.8	4	-1.9	4						
Average leg angle (deg)	13.0	5	17.2	5	13.1	4						
Hip moment impulse (N-m-s)	51.0	43	74.2	50	42.4	69						
Knee moment impulse (N-m-s)	14.8	49	6.1	33	18.7	68						
Ankle moment impulse (N-m-s)	219.0	105	215.0	80	268.0	114						

within subjects, using custom Matlab⁴ code. In the first level of the hierarchical model, relationships between the AP impulse with the average leg angle and hip, knee and ankle moment impulses were determined. Contralateral leg AP impulse was an additional variable analyzed in the first level model during pre-swing to investigate its ability to predict the ipsilateral AP impulse. In the second level, the relationships were further examined to determine dependence on leg (e.g., paretic or non-paretic) and level of asymmetry in the hemiparetic subjects, which was measured by the paretic step ratio (PSR = paretic step length/(non-paretic + paretic step length)). Hemiparetic subjects walking with an average PSR less than 0.47, between 0.47 and 0.53, and greater than 0.53 were classified in the low, symmetric and high PSR subgroups, respectively. Statistical significance was set at $p < 0.05$.

3. Results

Nine hemiparetic subjects walked with a low PSR (i.e., took shorter paretic than non-paretic steps), 16 subjects walked with a symmetric PSR, and 26 subjects walked with a high PSR. The overall and subgroup means and standard deviations of the AP impulses, average leg angle, and hip, knee and ankle moment impulses are presented in Table 1 and shown for representative subjects from each PSR subgroup in Fig. 2.

3.1. Relationships with the AP impulse during early propulsion

Leg angle during early propulsion was positively related to the AP impulse for the control group at each speed (Table 2). The hip and ankle moment impulses were negatively related to the AP impulse during early propulsion in the control group at 0.3 and

0.6 m/s (Table 2). Also, the knee moment impulse was positively related to the AP impulse in the control group at 0.3 and 0.6 m/s, but was negatively related at SS speed (Table 2).

For the hemiparetic group, high PSR subjects generated greater non-paretic AP impulses than paretic AP impulses during early propulsion (Table 3) and low PSR subjects generated lower non-paretic AP impulses than symmetric and high PSR subjects (Table 3).

Leg angle was positively related to the AP impulse during early propulsion (Table 2), although the magnitude of association was greater in the non-paretic leg (Table 3: coefficient = 1.28) than in the paretic leg (Table 3: coefficient = 0.86). The hip moment impulse was negatively related to the AP impulse for the hemiparetic group during early propulsion and this relationship was not different by leg or PSR subgroup (Table 2). The non-paretic knee moment impulse was positively related to the non-paretic AP impulse (Table 3), but the paretic knee moment and AP impulse was not significantly related. Also, the ankle moment impulse was negatively related to the AP impulse and this relationship was not different by leg or PSR subgroup (Table 2).

3.2. Relationships with the AP impulse during pre-swing

The AP impulse during pre-swing was positively related to leg angle and the ankle moment impulse at each speed for the control group (Table 2). Also, the hip moment impulse was negatively related to the AP impulse at each speed, and the knee moment impulse was positively related to the AP impulse in the control group at 0.3 and 0.6 m/s (Table 2).

⁴ Mathworks, 3 Apple Hill Dr, Natick, MA 01760-2098.

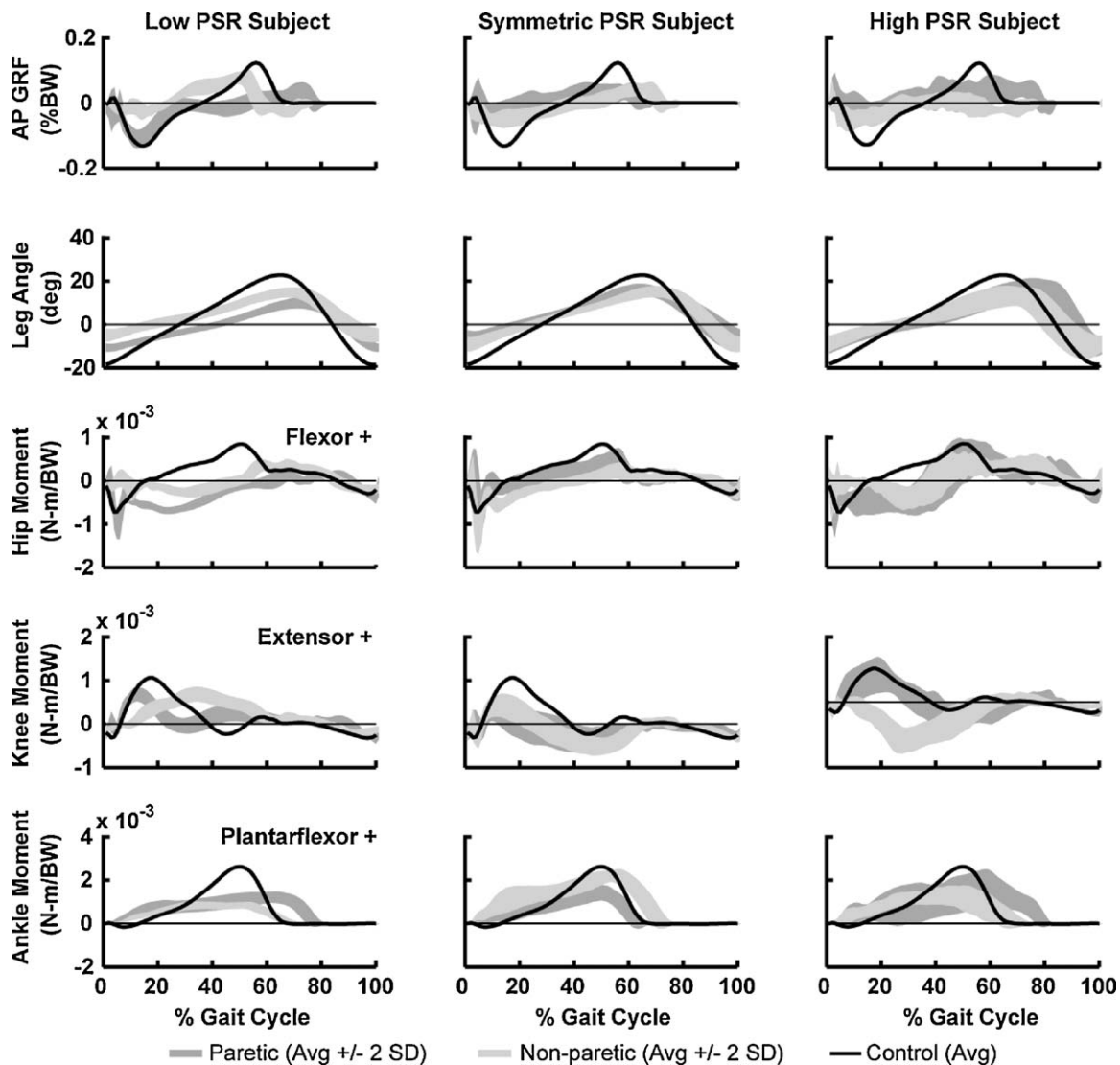


Fig. 2. Average (Avg.) anterior–posterior ground reaction forces (AP GRFs), leg angle, and joint moments for hemiparetic subjects representative of each paretic step ratio (PSR = paretic step length/(non-paretic + paretic step length)) subgroup and a speed-matched control. The low (PSR = 0.36), symmetric (PSR = 0.48) and high (PSR = 0.58) PSR subjects walked with self-selected treadmill speeds of 0.45, 0.6, and 0.3 m/s, respectively, and are compared with a control subject walking at 0.6, 0.6 and 0.3 m/s, respectively. Average paretic and non-paretic leg variables are shown with ± 2 standard deviations (SD) of the 30 s walking trial and are normalized to their corresponding gait cycles. Leg angle was defined as the angle between a line from the pelvis COM to the foot COM and vertical (positive when foot is posterior to the pelvis).

For the hemiparetic group during pre-swing, the non-paretic leg generated greater AP impulses than the paretic leg in the symmetric and high PSR subgroups (Table 1). As seen during early propulsion in the hemiparetic group, leg angle was positively related to the AP impulse with a stronger relationship in the non-paretic leg (Table 3: coefficient = 1.38) than in the paretic leg (Table 3: coefficient = 0.95), and the hip moment impulse was negatively related to the AP impulse independent of leg or PSR subgroup during pre-swing (Table 2). The non-paretic knee moment impulse was positively related to the non-paretic AP impulse, whereas the paretic knee moment impulse was negatively related to the paretic AP impulse (Table 3). For the low and symmetric PSR subjects, the non-paretic ankle moment impulse was positively related to the non-paretic AP impulse, and for the high PSR subjects, the paretic ankle moment impulse was negatively related to the paretic AP impulse (Table 3). Also during pre-swing, the paretic AP impulse was negatively related to the contralateral AP impulse (i.e., non-paretic AP impulse during early stance) (Table 3), but the non-paretic AP impulse was not related to

the contralateral AP impulse (i.e., paretic AP impulse during early stance).

4. Discussion

The primary goal of this study was to gain insight into mechanisms of propulsion generation by subjects with hemiparesis by identifying those biomechanical variables that predict AP impulses across subjects. Using regression analyses, we determined the biomechanical predictors with the potential to increase AP impulses and the necessary direction of change in the predictors.

4.1. Leg angle is an important predictor of the AP impulse

Leg angle was a significant predictor and positively related to the AP impulse from mid to late stance for the paretic, non-paretic and control legs at each speed highlighting the importance of leg extension in achieving adequate propulsion. Leg mechanics were

Table 2

First level coefficients of the two-level hierarchical regression model to predict AP impulses for the control group at 0.3, 0.6 m/s and self-selected (SS) speeds and for the hemiparetic group at SS speed during early propulsion and pre-swing. Predictive variables in the model were leg (e.g., paretic or non-paretic), average leg angle, and joint moment impulses. The contralateral AP impulse was an additional variable during pre-swing.

	Control			Hemiparetic
	0.3 m/s	0.6 m/s	SS	SS
Early propulsion				
Leg	1.75	1.14	−0.15	2.67*
Leg angle	0.94†	1.32†	0.96†	0.86†
Hip moment	−0.055*	−0.065*	−0.0080	−0.038†
Knee moment	0.044†	0.028*	−0.056†	0.0028
Ankle moment	−0.023†	−0.031†	−0.010	−0.019†
Pre-swing				
Leg	0.854	0.220	−3.509	13.95†
Leg angle	1.016†	1.457†	1.245†	0.95†
Hip moment	−0.059†	−0.067†	−0.090†	−0.063†
Knee moment	0.057†	0.031*	0.010	−0.018*
Ankle moment	0.024†	0.067†	0.107†	−0.024*
Contralateral AP impulse	−0.147*	−0.034	0.014	−0.065*

Significant predictors are indicated by:

* $p < .05$.

† $p < .001$.

Table 3

Second level coefficients that were significantly related to the AP impulse in the two-level hierarchical regression model for the hemiparetic group at self-selected speed during early propulsion and pre-swing. Second level effects determined dependence of first level relationships (Table 2) on leg (e.g., paretic or non-paretic) and paretic step ratio (PSR) subgroup (low: $PSR < 0.47$; symmetric: $0.47 \leq PSR \leq 0.53$; high: $PSR > 0.53$).

	Coefficient
Early propulsion effect	
High PSR, non-paretic leg	2.67*
Low vs. symmetric PSR, non-paretic leg	−4.79*
Low vs. high PSR, non-paretic leg	−5.33†
Non-paretic leg angle	1.28†
Paretic leg angle	0.86†
Non-paretic knee moment	0.040†
Pre-swing effect	
Low PSR	11.58†
Symmetric PSR	11.45†
High PSR	13.95†
Paretic leg angle	0.95†
Non-paretic leg angle	1.38†
Paretic knee moment	−0.018*
Non-paretic knee moment	0.038*
High PSR, paretic ankle moment	−0.024*
Low PSR, non-paretic ankle moment	0.041†
Symmetric PSR, non-paretic ankle moment	0.048†
Paretic leg, contralateral AP impulse	−0.065*

Significance of the effects are indicated by:

* $p < .05$.

† $p < .001$.

also found to be important in a recent study of accelerations during running that showed greater propulsive forces generated by subjects with a greater forward lean of the body [15]. A previous simulation analysis of healthy walking found that the gluteus maximus, vasti and soleus muscles make substantial contributions to hip and knee extension during single limb support [16]. These results suggest rehabilitation strategies aimed at increasing paretic propulsion should focus on these muscles to promote adequate paretic hip and knee extension. Specifically, emphasizing paretic hip extension in pre-swing with manual guidance during body-weight-supported treadmill training as suggested by Mulroy et al. [17], and also emphasizing paretic knee extension may increase paretic propulsion.

4.2. Joint moment relationships with the AP impulse

Joint moment impulses were also significant predictors of the AP impulse for each leg. The ankle moment impulse (plantar flexor positive) was negatively related to the AP impulse during early propulsion, which was consistent with simulation analyses of healthy walking showing negative contributions of the plantar flexors to the AP GRF during midstance [18]. The ankle moment impulse related positively to the AP impulse during pre-swing for the control and non-paretic legs, which is in agreement with studies showing the plantar flexors contribute to propulsion in late stance [6,18]. However, the relationship between the paretic ankle moment and AP impulse during pre-swing depended on PSR, suggesting different mechanisms of paretic AP impulse generation in this region based on PSR subgroup. The contribution of the paretic ankle moment to the AP GRF likely depends on the paretic leg angle since high PSR subjects, who achieve less paretic leg extension during pre-swing (Table 1), had a negative relationship.

The knee moment impulse (extensor positive) was positively related to the AP impulse for the non-paretic leg at SS speed and control legs at 0.3 and 0.6 m/s in both regions. This is consistent with a simulation of healthy walking that found the knee extensor moment contributes to forward progression from mid to late stance [19]. However, the paretic knee moment impulse was not related to the paretic AP impulse across hemiparetic subjects during early propulsion and negatively related during pre-swing. Similar to the paretic ankle moment, because extensor muscle force accelerates the COM when the foot is posterior to the pelvis, the relationship between the paretic knee moment and the AP impulse is also likely dependent on the paretic leg angle. In the control leg at SS speed, the knee moment impulse had a negative relationship with the AP impulse during early propulsion, and was not related to the ipsilateral AP impulse during pre-swing, which is likely due to the variability of the knee moment across subjects walking at different SS speeds as seen in previous studies [20,21].

The paretic, non-paretic and control hip moment impulses (flexor positive) were negatively related to their respective AP impulses in both regions. In healthy walking, the uniarticular hip flexors redistribute power from the trunk to the leg by decelerating the trunk and accelerating the leg forward during pre-swing [18]. Thus, increased output from the uniarticular hip flexors from late stance to pre-swing to advance the leg may have further decelerated the trunk with the net effect to decrease propulsion of the body COM. Furthermore, biarticular hip flexor activity may have decreased propulsion in late stance. A simulation study of healthy walking has shown that the rectus femoris decreases the propulsive AP impulse during late stance as it decelerates the leg more than it accelerates the trunk [18]. Also, increased EMG activity in rectus femoris during pre-swing has been associated with decreased AP impulse in persons with more severe hemiparesis [8].

4.3. Contralateral AP impulse relationships with the ipsilateral AP impulse

During ipsilateral and paretic pre-swing (double support phase), the contralateral and non-paretic AP impulses were negatively related to the ipsilateral and paretic AP impulses in the control subjects walking at 0.3 m/s and hemiparetic subjects, respectively. Decreased weight bearing on the paretic leg and a greater reliance on the non-paretic leg during double support has been previously reported in hemiparetic walking [22,23]. The significant relationship between the contralateral and ipsilateral AP impulse in the controls walking at 0.3 m/s was likely due to greater variability in these measures relative to their magnitude (Table 1) and may suggest decreased stability at the slow speed

[24]. Thus, improving paretic leg weight bearing and stability may decrease the contribution from the non-paretic leg and be important for increasing paretic propulsion during paretic pre-swing.

4.4. Limitations

We identified predictors of the AP impulse that can be targeted to improve the paretic leg's contribution to propulsion, although improved paretic propulsion may not correspond to increased walking speed. For example, decreasing paretic hip flexor output may decrease walking speed because some hemiparetic subjects with paretic ankle plantar flexor deficits increase the paretic hip flexor moment as a compensatory mechanism to increase speed [9]. A potential limitation of this study was that we analyzed treadmill walking, which has been shown to result in walking at a slower SS speed with a faster cadence and shorter stride length [25] compared to overground walking. However, a recent study compared the AP impulse between overground and treadmill walking and found there is no fundamental difference in propulsion mechanics [26]. In addition, the use of an instrumented treadmill was essential as it allowed for bilateral kinematic and kinetic data to be continuously monitored for a large number of consecutive cycles. Thus, we were able to accurately determine the steady-state walking pattern with its associated variability and increase the statistical power of the hierarchical regression models.

5. Conclusion

This study analyzed joint moments and pelvis–foot kinematics to identify the role of active muscle force production and indirect mechanics, respectively, in the generation of AP impulses in hemiparetic walking. Hierarchical regression models were used to determine the specific mechanisms that relate to propulsion generation in order to direct rehabilitation strategies aimed at increasing paretic propulsion. Increasing paretic leg extension and plantar flexor output and decreasing paretic hip flexor output from mid to late stance each have the potential to increase paretic propulsion in subjects with hemiparesis. Future studies using subject-specific modeling and simulation techniques will help validate these conclusions and provide further insight into the proposed mechanisms underlying propulsion generation in hemiparetic walking.

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Conflict of interest statement

None.

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