

Anterior-Posterior Ground Reaction Forces as a Measure of Paretic Leg Contribution in Hemiparetic Walking

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Background and Purpose—Walking after stroke is characterized by slow gait speed, poor endurance, reduced quality and adaptability of walking patterns, and an inability to coordinate the legs. Estimates based on mechanical work calculations have suggested that the paretic leg does 30% to 40% of the total mechanical work over the gait cycle, regardless of hemiparetic severity, but these work estimates may not describe the contribution of each leg to forward propulsion. The purpose of this study was to establish a quantifiable link between hemiparetic severity and paretic leg contribution to propulsion during walking, which we propose to quantify using a measure based on the anterior-posterior ground reaction forces (A-P GRFs).

Methods—A total of 47 participants with chronic hemiparesis walked at self-selected speeds to collect spatiotemporal parameters and 3D GRFs. A 16-person subset also participated in a pedaling protocol to compare A-P GRF measures to established measures of paretic leg output.

Results—A-P GRF measures were correlated with both walking speed and hemiparetic severity. These measures were also strongly correlated with positive work and net work values obtained during the pedaling task. The percentage of total propulsion generated by the paretic leg (P_p) was calculated and found to be 16%, 36%, and 49% for those with high, moderate, and low hemiparetic severity, respectively.

Conclusion— P_p was found to provide a quantitative measure of the coordinated output of the paretic leg. Further research on this measure of forward propulsion may lead to the provision of an effective tool for distinguishing functional compensation from physiological restitution. (*Stroke*. 2006;37:872-876.)

Key Words: hemiplegia ■ locomotion ■ motor activity

Poststroke hemiparesis results in a unilateral primary impairment of the paretic leg that results in a disrupted walking pattern. Therapeutic strategies for walking recovery have focused largely on the paretic leg because it exhibits a reduced muscular output, which is evidenced by decreased maximal voluntary contraction,¹ reduced electromyography (EMG) amplitudes during walking,² and a decline in mechanical work performed.³ However, there are limitations in available quantitative measures of strength (they are not specific to the walking task), EMG (it is difficult to synthesize information from multiple muscles) and mechanical work (eg, requires multiple assumptions⁴) such that currently available measures give an incomplete assessment of the coordinated output of the paretic leg during walking. Walking speed is the most widely used measure of performance; however, compensatory action by the nonparetic leg can result in a relatively functional walking speed despite poor coordination of the paretic leg. Although a training program may increase one's walking speed by making a compensatory

strategy more effective, current neurorehabilitation philosophies based on the principles of neuroplasticity are directed at the restitution of neurological deficits. Thus, a quantitative measure of the coordinated output of the paretic leg might predict the outcome of therapy; assist in evaluating the specific muscle coordination changes associated with various therapeutic interventions; and correlate with structural and functional studies of the nervous system such that the underlying mechanisms can be better understood.

Olney et al suggested that the paretic leg, regardless of hemiparetic severity, performs $\approx 40\%$ of the mechanical work of walking, as calculated from kinetic analyses based on intersegmental joint powers.³ However, these mechanical work estimates rely on assumptions as to the recovery of mechanical work from individual sources and intercompensation between sources⁴ and do not describe what functional tasks are being accomplished by the work. Forward dynamic simulation models have demonstrated that more of the mechanical work performed during a gait cycle is done in early

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single leg stance to raise the body's center of mass (COM) than occurs in double limb support (DLS) before swing, which primarily provides forward propulsion and swing initiation.⁵ The power produced during DLS likely decreases even more in those with slower walking speeds, implying that an even higher proportion of work is done to raise the COM. Currently, no adequate measure exists to examine the paretic leg contributions to the task of propelling the body forward during walking, which is an essential requirement of locomotion.⁶

Paretic limb work production has been studied previously using a well-controlled pedaling paradigm.^{7,8} This model has shown that the paretic leg produces significantly less mechanical work output than do healthy, age-matched controls.⁹ This net decrease in mechanical work output is a product of less positive work and more negative work being done by the paretic leg.⁹ Of particular interest is that the pedaling-derived measures of mechanical work seem to assess coordinated output independent of the need to support the body by providing postural stability as a result of the seated posture. As a result, the contribution of the paretic leg to the pedaling task in the most impaired subjects was found to be near 0, or even negative (ie, hindering task accomplishment that requires additional work done by the nonparetic leg). Thus, in contrast to the findings of Olney et al in walking, we were able to link hemiparetic severity to motor performance.¹⁰

Similarly, the anterior-posterior ground reaction forces (A-P GRFs) may represent an appropriate method of measuring the contribution of the paretic leg to the coordinated task of forward propulsion during walking. Previous studies have implemented A-P GRFs as a measure of the forward propulsion and braking in people with hemiparesis using a cane for ambulatory assistance,¹¹ but the A-P GRFs have not been used as a measure of the mechanical contribution of the paretic and nonparetic legs. In addition, we propose comparing the paretic leg coordinated output in walking to our previously derived measures for pedaling and propose that pedaling measures will provide confirming evidence of the importance and robustness of these walking measures. Specifically, we hypothesize that measures derived from the A-P GRF impulse (paretic and nonparetic propulsive impulse, paretic and nonparetic braking impulse, and paretic net propulsion) will correlate with gait speed, hemiparetic severity, and the positive and negative work measurements in pedaling.

Materials and Methods

The A-P GRF data presented in this study were collected (but not reported) as part of a larger study that investigated the links between gait characteristics and bone density in chronic stroke survivors.¹²

Individuals presenting with chronic stroke were recruited for this study at the Palo Alto Department of Veterans Affairs Medical Center. Forty-seven individuals with chronic hemiparesis (41 male; 6 female; 62.4 ± 10.2 (SD) years of age; time since stroke (years) = 4.3 ± 3.8 ; affected side left = 25, right = 22) participated in the study. A subset of this population also participated in a pedaling study in our laboratory.¹³ This sample of 16 included 14 males and 2 females, 9 with left hemiparesis and 7 with right hemiparesis; average age of 63.5 ± 6.6 years; average chronicity was 3.0 ± 1.4 years. Written informed consent was obtained from all participants for each study,

and the Stanford University administrative panel on human subjects in medical research approved both protocols.

Inclusion criteria were: unilateral weakness; <85 years of age; time since stroke >12 months; if female, ≥ 5 years past the onset of menopause; and ability to walk 10 m in ≤ 50 seconds without contact assistance. Exclusion criteria were: >1 previous cerebral vascular incident; inability to provide informed consent; use of osteoporosis drug or hormone replacement therapy within the past 5 years; history of leg fracture or pain; and the existence of any other medical condition that could affect bone mass.

Participants were characterized according to their level of hemiparetic severity, identified on the basis of the Brunnstrom motor recovery stages.¹⁴ These participants demonstrated a range of abilities to perform movements within and outside of extensor and flexor synergy patterns.¹⁴ Severe hemiparesis was defined as subjects rated as Brunnstrom stage 3 ($n=19$), moderate hemiparesis was defined as subjects rated as either a Brunnstrom stage 4 or 5 ($n=18$), and mild hemiparesis was defined as subjects rated Brunnstrom stage 6 ($n=10$).

Walking speeds were measured while each participant walked on a 4.3-m-long GAITRite portable walkway system (CIR Systems, Inc). Additionally, GRFs were measured throughout the stance phase for both the paretic and nonparetic legs as each participant walked at their self-selected speed along a 10-m walkway equipped with embedded force platforms (Advanced Medical Technology, Inc and Bertec). GRF data were acquired at 200 Hz and were filtered with a low-pass fourth order Butterworth filter at 20 Hz forward and backward in time. The A-P GRF component (normalized by each individual's body weight) was used in the subsequent analysis. Four to 15 trials were collected to assure adequate contact on the force platforms to determine the GRF and walking speed for each participant. When possible, multiple foot contacts were averaged to generate GRF values, but in 1 participant, only 1 trial could be analyzed because of inconsistent foot striking on the force plate.

A subset of the sample also participated in a separate experiment in which they were assessed on a cycle-ergometer to evaluate work production generated by each leg. The positive, negative, and total work (sum of positive and negative) were calculated for each lower extremity. The pedaling evaluations were completed with a custom 2-servomotor ergometer, which has been described previously in the literature.⁸ In the present pedaling trials, the servomotors were programmed to emulate conventional 2-legged pedaling, and toe clips were used to allow the hip flexors to generate power during the cycle.

The stance phase was separated into 4 bins to analyze impulse generation at various time points in the gait cycle: (1) DLS after paretic foot strike, (2) the first 50% of paretic single limb stance, (3) the second 50% of paretic single limb stance, and (4) DLS before paretic swing. Customized Matlab programs were written to process the data, and when possible raw data from 2 consecutive heel strikes were analyzed to examine the temporal relationship with the contralateral leg. When consecutive heel strikes were not collected, average temporal relationships were assumed to be representative of a subject's gait.

Variables derived from the A-P GRFs were defined as follows: (1) propulsive impulse is the time integral of the positive A-P GRFs; (2) braking impulse is the time integral of the negative A-P GRFs; and (3) net impulse is the sum of the propulsive impulse plus the braking impulse for each leg. Propulsive and braking impulses were also calculated within each bin. The percentage of total propulsion generated by the paretic leg, referred to as paretic propulsion (P_p), was calculated by dividing the propulsive impulse of the paretic leg by the sum of the paretic and nonparetic propulsive impulses.

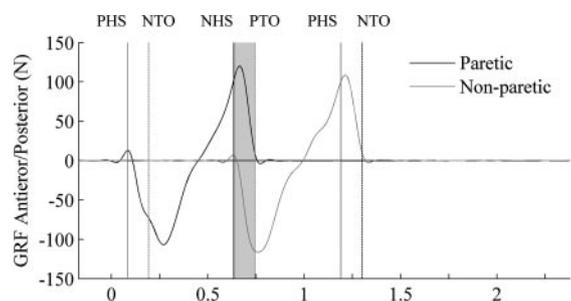
Data Analysis

Correlations between parametric variables were analyzed using the Pearson correlation coefficient, whereas correlations with hemiparetic severity levels were performed using the nonparametric Spearman correlation. All statistics were run using SPSS version 11.0 (SPSS, Inc.).

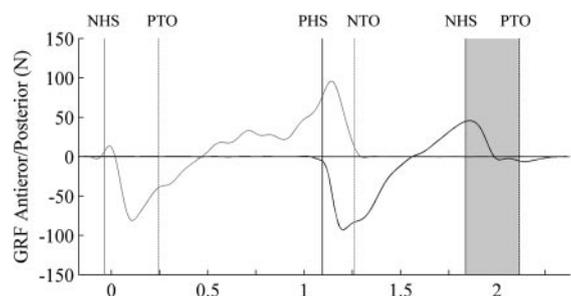
Results

Gait Characteristics

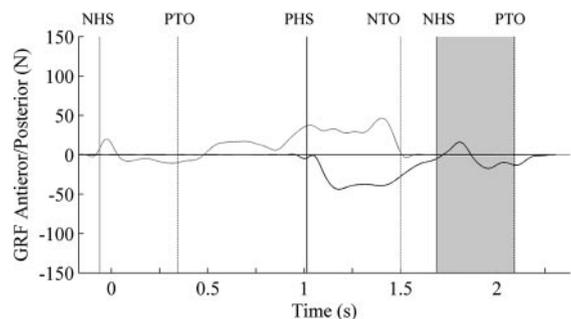
Figure 1 illustrates the A-P GRF tracing for 3 representative participants. In steady-state (constant speed) walking, the area



Mild Hemiparesis
 Propulsion_{Paretic} = 52.8%
 Gait Velocity = 1.20 m/s



Moderate Hemiparesis
 Propulsion_{Paretic} = 34.2%
 Gait Velocity = 0.60 m/s



Severe Hemiparesis
 Propulsion_{Paretic} = 8.9%
 Gait Velocity = 0.44 m/s

Figure 1. Comparison of the A-P GRFs for the paretic (dark lines) and nonparetic legs (gray lines) of subjects of differing hemiparetic severity. Positive values represent propulsion, and the positive area under the curve is the propulsive impulse. PHS indicates paretic heel strike; NTO, nonparetic toe off; NHS, nonparetic heel strike; PTO, paretic toe off. Increased hemiparetic severity was associated with decreased P_p and decreases in self-selected walking speed.

under the curve in the positive direction (propulsion) should roughly equal the area under the curve in the negative direction (braking) and the tracings of the 2 legs should be similar in shape and magnitude. Note that in the top participant, the paretic and nonparetic legs were fairly symmetrical. However, the more impaired subjects were asymmetrical. To maintain steady-state walking speeds, reduced net propulsion by the paretic leg has to be offset by increased propulsion in the nonparetic leg. As the graphs progress from mild to severe hemiparesis, there is a smaller percentage of P_p , corresponding with a slower walking speed.

Walking Speed

Walking speed was positively correlated with paretic propulsive impulse, nonparetic braking impulse, paretic net impulse, nonparetic net impulse, and the net impulse of Bin4 on the paretic leg (Table 1).

Hemiparetic Severity

Severity was significantly correlated with propulsive impulse, net impulse, and Bin4 net impulse in the paretic leg, and propulsive impulse, braking impulse, and net impulse in the nonparetic leg (Table 1).

Analyses then examined the effect of hemiparetic severity on P_p . Figure 2 illustrates that for those categorized as mild severity, the mean P_p is $\approx 49\%$. Those participants who demonstrated

moderate severity had a mean P_p of 36%, whereas those participants with severe hemiparesis had a mean P_p of only 16%.

All participants in this study were allowed to walk with the assistive or orthotic device that they normally use in everyday walking. Eight of 19 participants with severe hemiparesis used an ankle-foot orthosis (AFO), and 11 of the 19 used some form

TABLE 1. Correlations of Gait Characteristics With Walking Speed and Stroke Severity

Outcome Measure	Walking Speed*	Hemiparetic Severity#
Paretic propulsive impulse	$r=0.641, P=0.000$	$r=-0.650, P=0.000$
Paretic braking impulse	$r=-0.235, P=0.112$	$r=-0.162, P=0.276$
Nonparetic propulsive impulse	$r=0.140, P=0.350$	$r=0.467, P=0.001$
Nonparetic braking impulse	$r=0.696, P=0.000$	$r=0.507, P=0.000$
Paretic net impulse	$r=0.363, P=0.012$	$r=-0.659, P=0.000$
Nonparetic net impulse	$r=-0.431, P=0.002$	$r=0.753, P=0.000$
Paretic Bin4 net impulse	$r=0.748, P=0.000$	$r=-0.681, P=0.000$

*Pearson correlation coefficient; #Spearman correlation coefficient. Bolded values indicate significant differences.

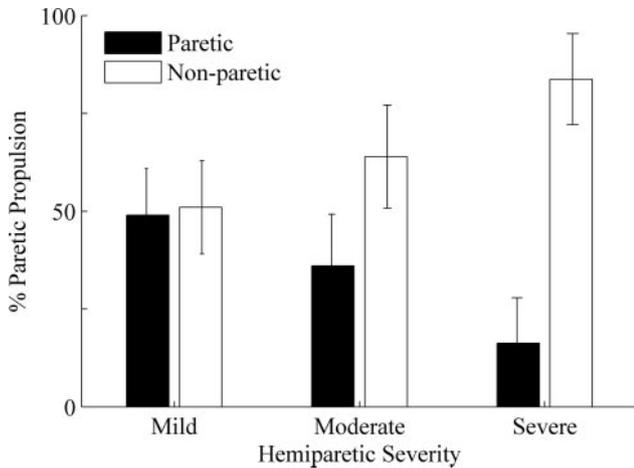


Figure 2. Comparison of the average propulsion (expressed as a percentage of the total propulsion) generated by the paretic (shaded bars; P_p) and nonparetic legs (white bars) of subjects of differing hemiparetic severity. There are substantial differences in the percent of P_p in those with severe and moderately severe hemiparesis when compared with those with mild severity. Compensation by the nonparetic leg is noticeable in the asymmetry shown by the moderate and severe groups. Error bars indicate SD for each variable.

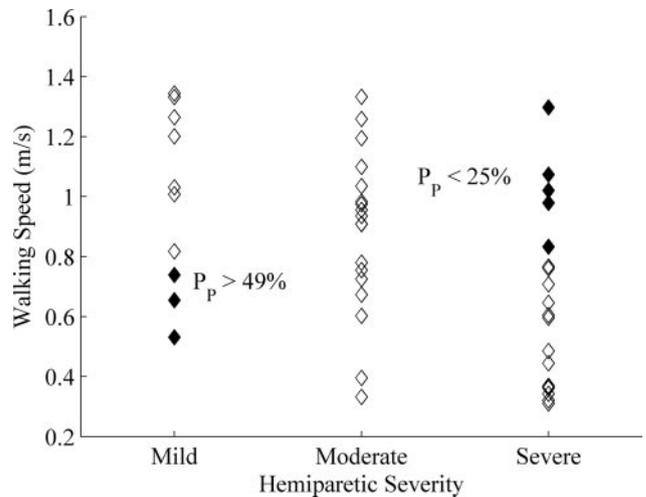


Figure 3. Individual walking speed data for subjects in each of the hemiparetic severity groups. Although there is a weak overall trend for walking speed to decrease with severity, the variability is substantial and the speed ranges in each of the groups overlap substantially. Five participants with severe hemiparesis are still able to achieve normal walking speeds (>0.8 m/s), but all demonstrate substantial decreases in P_p . Conversely, 3 participants with mild hemiparesis walked <0.8 m/s but have normal P_p ($>49\%$). These 8 participants are indicated with filled markers.

of unilateral assistive device. Analyses were done to see whether orthotic or assistive device usage affected the P_p . There was not a significant difference ($P=0.176$) between those that used an AFO ($P_p=12.07\%$) and those who did not ($P_p=19.32\%$). There was a nonsignificant difference ($P=0.74$) between those using assistive devices ($P_p=12.45\%$) and those who did not ($P_p=21.52\%$). Those participants who used neither an AFO nor an assistive device had a P_p of 21.14%.

P_p was significantly correlated with both speed ($r=0.551$; $P=0.000$) and with hemiparetic severity ($r=0.737$, $P=0.000$). However, note that 5 individuals with severe hemiparesis walked faster than the functionally significant 0.8 m/s,¹⁵ and all had $P_p \leq 25\%$ (Figure 3). Additionally, 3 individuals with mild severity walked more slowly than 0.8 m/s and all had $P_p \geq 49\%$. These 8 participants are indicated in Figure 3 with filled markers.

Pedaling Characteristics

Pedaling Subset

Sixteen individuals completed the full pedaling and gait evaluations, including work and force production results.

Correlations of Pedaling and Walking

Measurements of work production in pedaling (total work, positive work, and negative work) were correlated with the impulse generated during walking (paretic propulsive impulse, paretic braking impulse, paretic net impulse, and paretic net Bin4 impulse; Table 2).

Correlations of Pedaling and Walking With Hemiparetic Severity

Hemiparetic severity was positively correlated with total work done in pedaling ($r=0.798$; $P=0.000$), with positive work done in pedaling ($r=0.588$; $P=0.017$) and negative work done in pedaling ($r=0.791$; $P=0.000$).

Discussion

P_p was found to provide a quantitative measure of the coordinated output of the paretic leg that is sensitive to hemiparetic severity. The correlation between P_p and hemiparetic severity was strong, and there was a dramatic difference between those with severe hemiparesis (16% P_p) and a mild hemiparesis (49% P_p). These findings demonstrate that P_p levels are sensitive to hemiparetic severity, differing from mechanical work estimates that calculate work at a constant 40% regardless of severity.³ Reduced P_p by those with severe hemiparesis does not seem to be attributable solely to the use of an assistive or orthotic device because even those with severe hemiparesis not using assistive or orthotic devices demonstrated markedly reduced P_p (21.14%). In addition to P_p , the raw measures of walking presented here: paretic propulsive impulse, net paretic impulse, and net impulse in Bin4 are all sensitive to the severity of the hemiparesis, implying that the A-P GRF quantities are appropriate measures for assessing the paretic leg contribution to walking that are sensitive to severity. Additionally, these results also

TABLE 2. Walking and Pedaling Correlations

Paretic Leg: Pedaling	Paretic Leg: Walking	<i>r</i>	<i>P</i>
Total work	Propulsive impulse	0.588	0.017
	Net paretic impulse	0.550	0.027
	Net Bin4 impulse	0.748	0.001
Positive work	Propulsive impulse	0.613	0.012
	Net paretic impulse	0.631	0.009
	Net Bin4 impulse	0.661	0.005
Negative work	Braking impulse	0.064	0.813

Bolded values indicate significant differences.

corroborate previous findings correlating hemiparetic severity with the pedaling measures.

The overall aim of this article was to further our understanding of the contribution of the paretic leg to forward propulsion in hemiparetic walking. Previous work on hemiparetic interlimb coordination and contributions to total work using a pedaling paradigm has indicated that work measurements are sensitive to hemiparetic severity.⁷ Specifically, those with more severe hemiparesis produce less total work and encounter more resistance from the paretic limb than do those with less severe hemiparesis. Comparing A-P GRFs with pedaling work, we see some similarities in the task of walking as both total and positive work strongly correlate with propulsive impulse, net paretic impulse, and net impulse generated during Bin4, which is the most propulsive phase of the gait cycle.¹⁶

It is important to realize that in addition to the active generation of propulsive forces by muscles, there were also direct mechanical influences associated with the value of P_p achieved because of the expected strong relationship between foot placement and amount of propulsive impulse. If the leg were to act purely as a rigid strut (ie, GRF vector parallel to long axis of leg), as in an idealized inverted pendulum, the A-P GRF would be directly related to the position of the foot relative to the COM of the body (ie, anterior foot position produces posterior GRF, the posterior foot position produces an anterior force, and asymmetry between the percent of the stance phase with the foot anterior versus posterior would introduce a similar asymmetry in propulsive impulse). Thus, reduced propulsion in Bin4 is likely related to an inability to achieve adequate hip extension (eg, sufficiently posterior foot position) in addition to reduced active generation of propulsive GRF by the muscle forces. Note that the resistive impulse late in Bin4 that follows the generation of some propulsive impulse (Figure 1, bottom tracing) is unlikely to be related to the direct mechanics because the foot is likely behind the COM in this phase. Consequently, direct mechanical effects are not sufficient to explain P_p . In addition, the biomechanics underlie 1 of the differences between walking and the pedaling paradigm. Negative work in pedaling is likely attributable to resistance from the paretic leg, whereas braking in walking may be a mechanical response to having taken a longer stride with the paretic leg.

Strong correlations were seen with net impulse (eg, propulsion—resistance) in Bin4, the DLS before the swing of the paretic limb. Bin4 is important in the attainment of speed during walking, and DeQuervain illustrated that those with hemiparesis with the slowest gait velocity spend the most time in Bin4.¹⁷ This phase may be of particular importance in the act of progressing the body forward because it coincides with the burst of ankle power,³ much of which is stored mechanical energy from gastrocnemius and soleus activity and acts to propel the body forward.¹⁶ Both total work and positive work performed during pedaling showed the strongest correlation with GRF impulses in Bin4, and this phase also had the strongest correlation with hemiparetic severity.

Finally, it may be possible to use the P_p to document compensatory gait patterns. For example, 5 of those with a

severe hemiparesis had a walking speed >0.8 m/s but had a P_p of $\leq 25\%$, implying that they were achieving their velocity through some mechanism other than paretic leg contribution. These compensations to achieve functional velocities are not appreciated when examining walking speed alone, but may be important in assessing outcomes for a therapeutic intervention. A training program may increase one's walking speed by only making a compensatory strategy more effective, but current neurorehabilitation philosophies based on the principles of neuroplasticity are directed at the restitution of neurological deficits. Thus, P_p may be an effective tool in distinguishing functional compensation from physiological restitution.

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