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Evaluation of measurements of propulsion used to reflect changes in walking speed in individuals poststroke

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Abstract

Recent rehabilitation approaches for individuals poststroke have focused on improving walking speed because it is a reliable measurement that is associated with quality of life. Previous studies have demonstrated that propulsion, the force used to propel the body forward, determines walking speed. However, there are several different ways of measuring propulsion and no studies have identified which measurement best reflects differences in walking speed. The primary purposes of this study were to determine for individuals poststroke, which measurement of propulsion (1) is most closely related to their self-selected walking speeds and (2) best reflects changes in walking speed within a session. Participants (N=43) with chronic poststroke hemiparesis walked at their self-selected and maximal walking speeds on a treadmill. Propulsive impulse, peak propulsive force, and mean propulsive value (propulsive impulse divided by duration) were analyzed. In addition, each participant's cadence was calculated. Pearson correlation coefficients were used to determine the relationships between different measurements of propulsion versus walking speed as well as changes in propulsion versus changes in walking speed. Stepwise linear regression was used to determine which measurement of propulsion best predicted walking speed and changes in walking speed. The results showed that all 3 measurements of propulsion were correlated to walking speed, with peak propulsive force showed the strongest correlation. Similarly, when participants increased their walking speeds, changes in peak propulsive forces showed the strongest correlation to changes in walking speed. In addition, multiplying each measurement by cadence improved the correlations. The present study suggests that measuring peak propulsive

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force and cadence may be most appropriate of the variables studied to characterize propulsion in individuals poststroke.

Keywords

stroke; gait; propulsion; speed; ground reaction force

Background

Stroke is the leading cause of long term disability in the U.S (Go et al., 2014). Slow walking speed is a commonly observed functional deficit in individuals poststroke (Dickstein, 2008; Schmid et al., 2007). Because walking speed is associated with independence and quality of life (Dobkin et al., 2010; Perry et al., 1995), recent rehabilitation studies used walking speed as a primary outcome measure (Dobkin et al., 2010). Propulsive force is correlated to walking speed (Andriacchi et al., 1977) and increases with increased walking speed in individuals poststroke (Hsiao et al., 2015). Thus, recent poststroke rehabilitations approaches have emphasized the importance of measuring and targeting propulsion (Awad et al., 2014b; Phadke, 2012)

Propulsion, defined as the force used to propel the body forward, was measured in several different ways in previous studies. In particular, propulsive impulse, defined as the time integral of the anterior ground reaction force (AGRF), has been commonly used to characterize propulsion in recent studies for individuals poststroke (Beaman et al., 2010; Bowden et al., 2006; Kesar et al., 2014; Sousa et al., 2013; Turns et al., 2007). Propulsive impulse accounts for both propulsive force and the length of propulsive duration. Based on the impulse-momentum principle, impulse applied to a constant mass (body mass) would induce change in velocity. Thus, propulsive impulse may be associated with walking speed. Peak propulsive force is another measurement that has been used to study forward propulsion during walking (Andriacchi et al., 1977; Campanini and Merlo, 2009; Franz et al., 2014; Goble et al., 2003; Hanley and Bissas, 2014; Kesar et al., 2011; Nilsson and Thorstensson, 1989; Sacco et al., 2010; Simmonds et al., 2012) and running (Moore et al., 2012). Improvements in peak propulsive force was correlated to long-term walking ability in individuals poststroke (Awad et al., 2014a). Different from propulsive impulse, peak propulsive force does not account for propulsive duration and only captures the maximal force generated during the propulsive phase. Another way to characterize propulsion is “mean propulsive value”, defined as the propulsive impulse divided by its time duration (Campanini and Merlo, 2009). Mean propulsive value therefore represents the average amount of propulsive force generated per step during the propulsive phase of gait. Because force is the product of mass and acceleration, it is expected that increasing propulsive force applied to the body center of mass would increase forward acceleration.

Despite the increasing evidence supporting the utility of measurements of propulsion, no studies have identified which measurement of propulsion is most closely related to individuals' walking speeds for persons with stroke. Campanini and colleagues reported that both peak propulsive force and mean propulsive value were similarly correlated with height-

normalized walking speed in individuals poststroke. However, propulsive impulse was not reported in their study. In addition, if measurement of propulsion is responsible for walking speed, it is conceivable that changes in propulsion will be related to changes in walking speed. However, to date, the ability of each of these measurements of propulsion to reflect changes in walking speed in individuals poststroke has not been compared. The primary purposes of this study were to determine for individuals poststroke, which measurement of propulsion (1) is most closely related to their self-selected walking speeds and (2) best reflects changes in walking speed.

In the present study, we examined the relationships between walking speed and different measurements of propulsion in individuals poststroke: propulsive impulse, peak propulsive force, and mean propulsive value. In addition, because calculating propulsion per step does not account for the number of steps, we multiplied each measurement by cadence to quantify propulsion generated per second and tested whether accounting for cadence could enhance the sensitivity of measurements of propulsion to walking speed in individuals poststroke.

Methods

Participants

A total of 43 participants (age, 58.3 ± 11.8 years; time since stroke, 4.5 ± 6.5 years; 17 female; 16 right hemiparetic; self-selected walking speed, 0.7 ± 0.3 m/s) with poststroke lower extremity hemiparesis were included in this study (see Table 1 for inclusion/exclusion criteria). This study was approved by the Institutional Review Board of the University of Delaware and all participants provided written informed consent to participate in this study.

Gait Evaluation

Kinetic and kinematic data were collected via an 8-camera (120 Hz sampling rate) motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) as participants walked at their self-selected and fast speeds on a split-belt treadmill (Bertec Corp., Columbus, OH, USA) instrumented with 2 independent 6 degree of freedom force plates capturing at 1080 Hz. Self-selected walking speed was defined as the participant's comfortable over ground walking speed during a 10-meter walk test (Plummer et al., 2015) and fast walking speed was the fastest speed that participants could maintain for at least 4 minutes of continuous walking on the treadmill. Previous work has described in detail the gait analysis setup (Awad et al., 2014b; Kesar et al., 2014; Reisman et al., 2013). Participants wore an overhead support harness with no body weight support and used a handrail if needed for safety. Kinematic and kinetic data were filtered using a bi-directional Butterworth low-pass filter at 6 and 30 Hz, respectively. Changes during speed modulation were calculated as the differences between measurements at self-selected and fast walking speed. Peak propulsive force was defined as the maximal anterior ground reaction force (AGRF) normalized to body weight (see Figure 1). Propulsive impulse was the force-time integral of the anterior phase of the AGRF normalized to body weight. Mean propulsive value was calculated by dividing the propulsive impulse by its time duration. Cadence was calculated by the number of steps divided by the length of the trial duration. All data were averaged across strides with 30 seconds trial duration for a given speed.

Statistical Analysis

A sample size of 43 subjects with a power of 0.8 and an alpha of 0.05 would detect a significant R of 0.42. First, three different measurements of propulsion were calculated for the paretic limb: propulsive impulse (Ns), peak propulsive force (N), and mean propulsive value (N). In addition, each of these measurements of propulsion was multiplied by cadence (steps/s) to generate 3 additional measurements: propulsive impulse*cadence (N*steps), peak propulsive force*cadence (N*steps/s), and mean propulsive value*cadence (N*steps/s). The relationships between self-selected walking speed and each of the above measurements of propulsion were analyzed by using Pearson correlation coefficients to determine whether each measurement was related to individuals' walking speed. Next, the relationships between changes in each measurement of propulsion as individuals modulated their speeds from their self-selected to fast walking speed versus their actual changes in walking speed were analyzed to determine the sensitivity of each measurement to changes in walking speed. Finally, stepwise linear regression analysis was used to determine the strongest predictor for self-selected walking speed and changes in walking speed. In the stepwise linear regression procedure, each variable was entered in sequence and was retained if it contributed significantly to the model. All other variables in the model were re-tested and were removed if they no longer contributed significantly to the model. The significance level was set at an alpha of 0.05. All statistics were run using SPSS (version 23.0, SPSS, Inc.).

Results

All measurements showed significant correlations with self-selected walking speed ($p < 0.01$, Figure 2). The r-value for propulsive impulse, peak propulsive force, and mean propulsive value versus walking speed were 0.58, 0.85, and 0.81, respectively. When multiplied by cadence, all 3 measurements showed greater correlations to walking speed compared to individual measurements without cadence (Figure 2 D-F). The r-value for propulsive impulse*cadence, peak propulsive force*cadence, and mean propulsive value*cadence versus walking speed were 0.73, 0.9, and 0.85, respectively. Results from stepwise linear regression revealed that peak propulsive force* cadence was the strongest predictor ($F=174.36$, $R^2=0.81$) of walking speed. Adding other variables did not contribute significantly to the prediction of self-selected walking speed (see Table 2).

Average walking speed increased from 0.69 to 0.86 (m/s) during the within session speed modulation. The r-value for changes in propulsive impulse, peak propulsive force, and mean propulsive value versus changes in walking speed were 0.1, 0.62, and 0.44, respectively (Figure 3). When multiplied by cadence, the r-value for changes in propulsive impulse*cadence, peak propulsive force*cadence, and mean propulsive value*cadence versus changes in walking speed were 0.2, 0.68, and 0.57, respectively. Results from stepwise linear regression analysis showed that the change in peak propulsive force*cadence was the strongest predictor for changes in walking speed ($F=24.83$, $R^2=0.46$). Adding other variables did not contribute significantly to the prediction of changes in walking speed (see Table 2).

Because our results showed that only 46% of the variances in changes in walking speed were explained by the best predictor (peak propulsive force*cadence), we calculated the sum of

paretic and non-paretic peak propulsive forces to see if more variances in changes in walking speed could be explained by accounting for the non-paretic propulsive force. The results showed that the r -value between both limbs' peak propulsive force*cadence versus walking speed was 0.92 (Figure 4). The r -value between changes in both limbs' peak propulsive force*cadence versus changes in walking speed was 0.75.

Discussion

In the present study, the relationships between different measurements of propulsion and walking speed were examined. Amongst all the measurement of propulsion, peak propulsive force*cadence showed the strongest correlation with walking speed. During speed modulation, only changes in peak propulsive force and mean propulsive value reflected changes in walking speed, with changes in peak propulsive force*cadence best reflected changes in walking speed. These findings suggest that measuring peak propulsive force and cadence may be more appropriate to assess differences in walking speed in individuals poststroke.

Consistent with previous cross-sectional studies, our results showed all measurements of propulsion were correlated with walking speed (Bowden et al., 2006; Campanini and Merlo, 2009; Hsiao et al., 2015). In addition, the relationships between peak propulsive force and mean propulsive value versus walking speed were stronger compared to propulsive impulse (Figure 2 A-C). Increases in propulsive impulse could be achieved by either increasing propulsive force or time. However, increases in propulsive time may not necessarily increase walking speed. For example, participants with slow walking speed could spend a longer period on each stride, result in a greater propulsive impulse per step. This large impulse may not translate to a greater walking speed, partly due to the slow cadence. Indeed, compared to propulsive impulse, the measurement of propulsive impulse*cadence has substantially enhanced the correlation between propulsive impulse and walking speed (Figure 2 A and D, R^2 increased from 0.34 to 0.54). Thus, calculating propulsive impulse per step alone may not be sufficient for reflecting gait speed.

Interestingly, during speed modulation, change in propulsive impulse, the most commonly used measurement of propulsion for individuals poststroke, was not correlated to changes in walking speed. Similar to our previous discussion, the dependency of propulsive impulse on propulsive duration also likely hinders its ability to reflect the differences in walking speed. Because the stance duration decreases as walking speed increases during speed modulation (Hebenstreit et al., 2015), the force-time integral of propulsive force may not increase with walking speed. As a result, changes in propulsive impulse may not be sensitive to changes in walking speed. Indeed, this was supported by the evidence that mean propulsive value, which was calculated from propulsive impulse divided by its duration, showed a much stronger correlation with walking speed and greater sensitivity to changes in walking speed. In contrast to propulsive impulse, peak propulsive force increased to compensate for the shorter stance propulsive duration at faster walking speeds and, therefore, better reflected changes in walking speed. In addition, our results extended previous studies that suggested that cadence should be considered when studying ground reaction forces (Martin and Marsh, 1992) by demonstrating that accounting for cadence could enhance the ability of

measurements of propulsion to reflect changes in walking speed in individuals poststroke. (Figure 3 E and F). Taken together, results from the present study therefore suggest that peak propulsive force*cadence may be the most appropriate of the variables studied to characterize propulsion and that caution may be needed when calculating propulsive impulse per step to study changes in walking speed in individuals poststroke.

Although peak propulsive force*cadence showed the strongest correlation with walking speed, only 46% of the variance in changes in walking speed was explained. Because asymmetry in propulsion was commonly observed in individuals poststroke (Bowden et al., 2006), propulsion from the non-paretic limb could also influence walking speed (Hsiao et al., 2015). Our results demonstrated that accounting for both limbs' peak propulsive forces and cadence further enhanced the ability of measurement of propulsion to reflect changes in walking speed (Figure 4B).

There are limitations in this study. Because of safety, our participants were allowed to use the handrail if needed. The use of handrail can affect the ground reaction force during walking. For example, participant #34 used the handrail during his fast walking speed but not during self-selected speed. As a result, this participant showed a negative change in both limbs' propulsive force and a positive change in walking speed during speed modulation (Figure 4B). Excluding this participant would increase the R^2 from 0.57 to 0.67 for the correlation between changes in both limbs' peak propulsive force*cadence and changes in walking speed (Figure 4B). We did not, however, exclude the data for this participant because they were not statistical outliers. Nevertheless, although the use of handrail could decrease the correlation, measuring peak propulsive forces and cadence still explained the majority of the variances in changes in walking speed. In addition, eliminating participants who used the handrail would bias the study sample towards individuals with higher levels of poststroke walking recovery. Another limitation is that the present study focused on individuals poststroke. Thus, findings from this study may not be generalizable to other populations.

Conclusions

This is the first study that investigated the ability of different measurements of propulsion to reflect changes in walking speed within a session in individuals poststroke. In addition, the effect of incorporating cadence with propulsion to predict walking speed was studied. Our results showed that for persons with stroke, peak propulsive force is most closely related to walking speed and that the measurement combining cadence and propulsion can best reflect changes in walking speed. Findings from this research could inform clinicians and researchers to use the appropriate measurement of propulsion for rehabilitation interventions that target increasing walking speed for individuals poststroke.

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References

- Andriacchi TP, Ogle Ja, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *J Biomech.* 1977; 10:261–268. DOI: 10.1016/0021-9290(77)90049-5 [PubMed: 858732]
- Awad LN, Binder-Macleod SA, Pohl RT, Reisman DS. Paretic propulsion and trailing limb angle are key determinants of long-distance walking function after stroke. *Neurorehabil Neural Repair.* 2015; 29:499–508. DOI: 10.1177/1545968314554625 [PubMed: 25385764]
- Awad LN, Reisman DS, Kesar TM, Binder-Macleod SA. Targeting paretic propulsion to improve poststroke walking function: A preliminary study. *Arch Phys Med Rehabil.* 2014; 95:840–848. DOI: 10.1016/j.apmr.2013.12.012 [PubMed: 24378803]
- Beaman CB, Peterson CL, Neptune RR, Kautz SA. Differences in self-selected and fastest-comfortable walking in post-stroke hemiparetic persons. *Gait Posture.* 2010; 31:311–6. DOI: 10.1016/j.gaitpost.2009.11.011 [PubMed: 20006505]
- Bowden MG, Balasubramanian CK, Neptune RR, Kautz SA. Anterior-posterior ground reaction forces as a measure of paretic leg contribution in hemiparetic walking. *Stroke.* 2006; 37:872–876. [PubMed: 16456121]
- Campanini I, Merlo a. Reliability, smallest real difference and concurrent validity of indices computed from GRF components in gait of stroke patients. *Gait Posture.* 2009; 30:127–31. DOI: 10.1016/j.gaitpost.2009.03.011 [PubMed: 19428254]
- Dickstein R. Rehabilitation of gait speed after stroke: a critical review of intervention approaches. *Neurorehabil Neural Repair.* 2008; 22:649–660. [PubMed: 18971380]
- Dobkin BH, Plummer-D'Amato P, Elashoff R, Lee J. International randomized clinical trial, stroke inpatient rehabilitation with reinforcement of walking speed (SIRROWS), improves outcomes. *Neurorehabil Neural Repair.* 2010; 24:235–242. [PubMed: 20164411]
- Franz JR, Maletis M, Kram R. Real-time feedback enhances forward propulsion during walking in old adults. *Clin Biomech.* 2014; 29:68–74. DOI: 10.1016/j.clinbiomech.2013.10.018
- Go AS, Mozaffarian D, Roger VL, Benjamin EJ, Berry JD, Blaha MJ, Dai S, Ford ES, Franco S, Fullerton HJ, Gillespie C, Hailpern SM, Heit Ja, Howard VJ, Huffman MD, Judd SE, Kissela BM, Kittner SJ, Lackland DT, Lichtman JH, Lisabeth LD, Mackey RH, Magid DJ, Marcus GM, Marelli A, Matchar DB, McGuire DK, Mohler ER, Moy CS, Mussolino ME, Neumar RW, Nichol G, Pandey DK, Paynter NP, Reeves MJ, Sorlie PD, Stein J, Towfighi A, Turan TN, Virani SS, Wong ND, Woo D, Turner MB. Heart Disease and Stroke Statistics--2014 Update: A Report From the American Heart Association. *Circulation.* 2014; 129:e28–e292. DOI: 10.1161/01.cir.0000441139.02102.80 [PubMed: 24352519]
- Goble DJ, Marino GW, Potvin JR. The influence of horizontal velocity on interlimb symmetry in normal walking. *Hum Mov Sci.* 2003; 22:271–283. DOI: 10.1016/S0167-9457(03)00047-2 [PubMed: 12967758]
- Hanley B, Bissas A. Ground reaction forces of Olympic and World Championship race walkers. *Eur J Sport Sci.* 2014; 16:50–56. DOI: 10.1080/17461391.2014.984769 [PubMed: 25429613]
- Hebenstreit F, Leibold A, Krinner S, Welsch G, Lochmann M, Eskofier BM. Effect of walking speed on gait sub phase durations. *Hum Mov Sci.* 2015; 43:118–124. DOI: 10.1016/j.humov.2015.07.009 [PubMed: 26256534]
- Hsiao H, Awad LN, Palmer JA, Higginson JS, Binder-Macleod SA. Contribution of Paretic and Nonparetic Limb Peak Propulsive Forces to Changes in Walking Speed in Individuals Poststroke. *Neurorehabil Neural Repair.* 2015; 30:743–752. DOI: 10.1177/1545968315624780 [PubMed: 26721869]
- Kesar TM, Reisman DS, Perumal R, Jancosko AM, Higginson JS, Rudolph KS, Binder-Macleod SA. Combined effects of fast treadmill walking and functional electrical stimulation on post-stroke gait. *Gait Posture.* 2011; 33:309–313. [PubMed: 21183351]
- Kesar TM, Sauer MJ, Binder-Macleod SA, Reisman DS. Motor Learning During Poststroke Gait Rehabilitation: A Case Study. *J Neurol Phys Ther.* 2014; 38:183–190. DOI: 10.1097/NPT.0000000000000047 [PubMed: 24933501]

- Martin PE, Marsh AP. Step length and frequency effects on ground reaction forces during walking. *J Biomech.* 1992; 25:1237–1239. DOI: 10.1016/0021-9290(92)90081-B [PubMed: 1400525]
- Moore IS, Jones AM, Dixon SJ. Mechanisms for improved running economy in beginner runners. *Med Sci Sports Exerc.* 2012; 44:1756–1763. DOI: 10.1249/MSS.0b013e318255a727 [PubMed: 22525760]
- Nilsson J, Thorstensson A. Ground reaction forces at different speeds of human walking and running. *Acta Physiol Scand.* 1989; 136:217–227. DOI: 10.1111/j.1748-1716.1989.tb08655.x [PubMed: 2782094]
- Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. *Stroke.* 1995; 26:982–989. [PubMed: 7762050]
- Phadke CP. Immediate Effects of a Single Inclined Treadmill Walking Session on Level Ground Walking in Individuals After Stroke. *Am J Phys Med Rehabil.* 2012; 91:337–345. DOI: 10.1097/PHM.0b013e31823cabe3 [PubMed: 22173086]
- Plummer P, Behrman AL, Duncan PW, Spigel P, Saracino D, Martin J, Fox E, Thigpen M, Kautz SA. Effects of stroke severity and training duration on locomotor recovery after stroke: a pilot study. *Neurorehabil Neural Repair.* 2015; 21:137–151. DOI: 10.1177/1545968306295559
- Reisman DS, Kesar TM, Perumal R, Roos MA, Rudolph KS, Higginson JS, Helm E, Binder-MacLeod SA. Time course of functional and biomechanical improvements during a gait training intervention in persons with chronic stroke. *J Neurol Phys Ther.* 2013; 37:159–65. DOI: 10.1097/NPT.000000000000020 [PubMed: 24189337]
- Sacco ICN, Akashi PMH, Hennig EM. A comparison of lower limb EMG and ground reaction forces between barefoot and shod gait in participants with diabetic neuropathic and healthy controls. *BMC Musculoskelet Disord.* 2010; 11:24. doi: 10.1186/1471-2474-11-24 [PubMed: 20128894]
- Schmid A, Duncan PW, Studenski S, Lai SM, Richards L, Perera S, Wu SS. Improvements in speed-based gait classifications are meaningful. *Stroke.* 2007; 38:2096–100. DOI: 10.1161/STROKEAHA.106.475921 [PubMed: 17510461]
- Simmonds MJ, Lee CE, Etnyre BR, Morris GS. The influence of pain distribution on walking velocity and horizontal ground reaction forces in patients with low back pain. *Pain Res Treat.* 2012; 2012:214980. doi: 10.1155/2012/214980 [PubMed: 22550576]
- Sousa ASP, Silva A, Santos R, Sousa F, Tavares JMRS. Interlimb coordination during the stance phase of gait in subjects with stroke. *Arch Phys Med Rehabil.* 2013; 94:2515–2522. DOI: 10.1016/j.apmr.2013.06.032 [PubMed: 23871877]
- Turns LJ, Neptune RR, Kautz SA. Relationships between muscle activity and anteroposterior ground reaction forces in hemiparetic walking. *Arch Phys Med Rehabil.* 2007; 88:1127–1135. [PubMed: 17826457]

List of Abbreviations

AGRF Anterior ground reaction force

Figure 1.

Illustration for measurements of propulsion. Peak propulsive force was defined as the maximal anterior ground reaction force (AGRF) normalized to body weight. Propulsive impulse was the force-time integral of the AGRF normalized to body weight. Mean propulsive value was calculated by dividing the propulsive impulse by its time duration.

Figure 2.

Relationships between measurements of propulsion and self-selected walking speed. (A) Propulsive impulse versus self-selected walking speed. (B) Peak propulsive force versus self-selected walking speed. (C) Mean propulsive value versus self-selected walking speed. (D) Propulsive impulse*cadence versus self-selected walking speed. (E) Peak propulsive force*cadence versus self-selected walking speed. (F) Mean propulsive value*cadence versus self-selected walking speed. “BW” denotes body weight, and “cad” denotes cadence. All correlations were significant ($p < 0.01$).

Figure 3.

Relationships between measurements of *changes* in propulsion and *changes* in walking speed during within session speed modulation. (A) Changes in propulsive impulse versus changes in walking speed. (B) Changes in peak propulsive force versus changes in walking speed. (C) Changes in mean propulsive value versus changes in walking speed. (D) Changes in propulsive impulse*cadence versus changes in walking speed. (E) Changes in peak propulsive force*cadence versus changes in walking speed. (F) Changes in mean propulsive value*cadence versus changes in walking speed. “BW” denotes body weight, and “cad” denotes cadence. Significant correlations were observed in panel B, C, E and F ($p < 0.01$).

Figure 4.

Relationship between the sum of paretic and non-paretic peak propulsive force*cadence versus walking speed. (A) Both limbs' peak propulsive force*cadence versus walking speed. (B) Changes in both limbs' peak propulsive force versus changes in walking speed. “BW” denotes body weight, and “cad” denotes cadence. Significant correlations were observed in both panels ($p < 0.01$). The dashed circle denotes the participant (#34) that showed positive changes in walking speed and negative changes in peak propulsive force.

Table 1

Participants' inclusion/exclusion criteria.

Inclusion criteria	Exclusion criteria
A single cortical or subcortical stroke A poststroke duration of at least 6 months The ability to ambulate without the assistance of another individual Sufficient cognitive function to follow instruction and communicate with the investigators The ability to walk for 6 min without orthotic support Sufficient passive dorsiflexion range of motion to position the ankle in a Neutral position with the knee extended Sufficient passive hip extension to extend the hip 10°	Had a history of multiple strokes Cerebellar stroke Lower extremity joint replacement Bone or joint problems that limited their ability to walk A resting heart rate outside of the range of 40–100 beats per minute A resting blood pressure outside of the range of 90/60 to 170/90 mm Hg Neglect Hemianopia Unexplained dizziness during the past 6 months Chest pain or shortness of breath without exertion

Table 2

Results from stepwise linear regression to predict self-selected walking speed and changes in walking speed.

	Self-selected walking speed	p-value	walking speed	p-value
Predictor	Peak*cad	<i><0.01</i>	Peak*cad	<i><0.01</i>
Variables with non-significant contribution to overall model fit	Imp	<i>0.43</i>	Peak	<i>0.85</i>
	Peak	<i>0.56</i>	Mean	<i>0.91</i>
	Mean	<i>0.73</i>	Mean*cad	<i>0.64</i>
	Imp*cad	<i>0.48</i>		
	Mean*cad	<i>0.67</i>		

= the change from self-selected to fast walking speed, Peak = peak propulsive force, Imp = propulsive impulse, Mean = mean propulsive value, Cad = cadence. Note that changes in propulsive impulse and changes in propulsive impulse*cadence were excluded because they were not correlated with changes in walking speed (Figure 3A and D).