

Marquette University

e-Publications@Marquette

Physical Therapy Faculty Research and
Publications

Physical Therapy, Department of

4-2022

Symmetry Is Associated With Interlimb Coordination During Walking and Pedaling After Stroke

Brice T. Cleland
Marquette University

Sheila M. Schindler-Ivens
Marquette University, sheila.schindler-ivens@marquette.edu

Follow this and additional works at: https://epublications.marquette.edu/phys_therapy_fac



Part of the [Physical Therapy Commons](#)

Recommended Citation

Cleland, Brice T. and Schindler-Ivens, Sheila M., "Symmetry Is Associated With Interlimb Coordination During Walking and Pedaling After Stroke" (2022). *Physical Therapy Faculty Research and Publications*. 189.

https://epublications.marquette.edu/phys_therapy_fac/189

Marquette University

e-Publications@Marquette

Physical Therapy Faculty Research and Publications/College of Health Sciences

This paper is NOT THE PUBLISHED VERSION.

Access the published version via the link in the citation below.

Journal of Neurologic Physical Therapy, Vol. 46, No. 2 (April 2022): 81-87. [DOI](#). This article is © Lippincott Williams & Wilkins, Inc. and permission has been granted for this version to appear in [e-Publications@Marquette](#). Lippincott Williams & Wilkins, Inc. does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from Lippincott Williams & Wilkins, Inc.

Symmetry Is Associated with Interlimb Coordination During Walking and Pedaling After Stroke

Brice T. Clelend

Department of Physical Therapy, College of Health Sciences, Marquette University, Milwaukee, WI

Sheila Schindler-Ivens

Department of Physical Therapy, College of Health Sciences, Marquette University, Milwaukee, WI

Abstract

Background and Purpose:

Asymmetry during walking may be explained by impaired interlimb coordination. We examined these associations: (1) propulsive symmetry with interlimb coordination during walking, (2) work symmetry with interlimb coordination during pedaling, and (3) work symmetry and interlimb coordination with clinical impairment.

Methods:

Nineteen individuals with chronic stroke and 15 controls performed bilateral, lower limb pedaling with a conventional device and a device with a bisected crank and upstroke assistance. Individuals with stroke walked on a split-belt treadmill. Measures of symmetry (%Propulsion_{walk}, %Work_{ped}) and interlimb phase coordination index (PCI_{walk}, PCI_{ped}) were computed. Clinical evaluations were the lower extremity Fugl-Meyer (FMLE) and walking speed. Associations were assessed with Spearman's rank correlations.

Results:

Participants with stroke displayed asymmetry and impaired interlimb coordination compared with controls ($P \leq 0.001$). There were significant correlations between asymmetry and impaired interlimb coordination (walking: $R^2 = 0.79$, $P < 0.001$; pedaling: $R^2 = 0.62$, $P < 0.001$) and between analogous measures across tasks (%Work_{ped}, %Propulsion_{walk}: $R^2 = 0.41$, $P = 0.01$; PCI_{ped}, PCI_{walk}: $R^2 = 0.52$, $P = 0.003$). Regardless of task, asymmetry and interlimb coordination were correlated with FMLE ($R^2 \geq 0.48$, $P \leq 0.004$) but not walking speed. There was larger within group variation for %Propulsion_{walk} than %Work_{ped} ($Z = 2.6$, $P = 0.005$) and for PCI_{ped} than PCI_{walk} ($Z = 3.6$, $P = 0.003$).

Discussion and Conclusions:

Pedaling may provide useful insights about walking, and impaired interlimb coordination may contribute to asymmetry in walking. Pedaling and walking provide distinct insights into stroke-related impairments, related to whether the task allows compensation (walking > pedaling) or compels paretic limb use (pedaling > walking). Pedaling a device with a bisected crank shaft may have therapeutic value.

Video Abstract available for more insight from the authors (see the Video, Supplemental Digital Content 1, available at: <https://links.lww.com/JNPT/A365>).

Introduction

After stroke, the propulsion of walking and other lower limb movements is achieved predominately by the nonparetic limb.^{1–5} This observation is perplexing because most stroke survivors regain considerable movement of the paretic lower limb,^{6–10} and the bilateral nature of lower limb function offers plentiful opportunities for paretic limb use. The work described here seeks to explain the persistence of asymmetric propulsion during walking in people with chronic stroke.

In a recent study examining this phenomenon, we found that work asymmetry (paretic < nonparetic) in the lower limbs of people with stroke was more strongly associated with abnormal interlimb coordination than impaired motor output of the paretic limb.¹¹ We suggested that rehabilitation strategies aimed at retraining interlimb coordination may reduce work asymmetries and improve paretic motor output during bilateral lower limb movements. Such strategies may improve walking given that interlimb coordination is important for transitioning between phases of the gait cycle (eg, stance-to-swing), maintaining stability, and responding to perturbations.¹² Important to our conclusions, observations were derived from a split-crank pedaling paradigm that was designed to distinguish between impaired interlimb coordination and paretic motor output. Previous studies have reported work asymmetry during pedaling, but mostly in the context of bilateral coupled pedaling.^{3–5}

Pedaling is a useful model for walking because both tasks involve continuous, reciprocal, multijoint movement of both limbs. Still, it remains unclear whether our conclusions from pedaling extend to walking. One previous study found an association between work symmetry during pedaling and propulsive symmetry during walking,² but no studies have evaluated the association between interlimb coordination during pedaling and walking or the association between interlimb coordination and propulsive symmetry during walking.

In the present study, we addressed these issues by measuring symmetry and interlimb coordination during walking and pedaling. Our purpose was 3-fold. First, we sought to determine whether asymmetric propulsion during walking is associated with abnormal interlimb coordination during the same task. Next, we asked whether work asymmetry and impaired interlimb coordination during pedaling are associated with analogous impairments in walking. Finally, we asked whether these measures are associated with clinical measures of stroke-related impairment. We hypothesized that propulsive asymmetry would be associated with abnormal interlimb coordination during walking; symmetry and interlimb coordination would be associated with analogous measures between walking and pedaling; and asymmetry and abnormal interlimb coordination would be associated with greater stroke-related impairment.

Methods

Participants

As summarized in Table 1, 19 individuals with chronic stroke and 15 controls participated. All were free of illness, injury, and neurological disorders except for stroke. All provided written informed consent prior to participating. Study procedures were approved by the Marquette University Institutional Review Board. Based on the association between work symmetry and interlimb coordination during pedaling ($R^2 = 0.45$),¹¹ we determined that a sample size of 19 individuals with stroke was necessary to detect a similar relationship during walking ($\alpha = 0.05$, $\beta = 0.10$).

Table 1. - Participant Demographics and Clinical Measures^a

	Stroke (n = 19)	Control (n = 15)
Age, y	59 (11)	67 (8) ^b
Sex (male/female)	11/8	7/8
Height, m	1.75 (0.10)	1.72 (0.10)
Mass, kg	85 (15)	79 (15)
BMI, kg/m ²	28 (4)	27 (5)
Time since stroke, y	12 (6), range: 3-24	
Stroke type (ischemic/hemorrhagic)	15/4	
Stroke location (cortical/subcortical)	12/5	
Paretic limb (left/right)	11/8	
Walking speed, m/s	0.87 (0.30)	
FMLE	25 (6)	

Abbreviations: BMI, body mass index; FMLE, Fugl-Meyer Lower Extremity, motor portion.

^aDemographic characteristics are shown for the stroke and control group. Values are mean (SD).

^b $P < 0.05$ between group comparison.

Materials, Measures, and Procedures

Propulsive symmetry and interlimb coordination during walking were evaluated in the stroke group. Participants walked at a self-selected, comfortable rate on an instrumented, split-belt treadmill (FIT, Bertec Corporation, Ohio). Both belts were moving at the same speed. Participants were encouraged to walk without upper limb support but could use the handrails for safety. A ceiling-mounted harness with no body-weight support was also employed for safety. Force plates mounted beneath each belt recorded ground reaction forces in the vertical (GRFz) and anterior/posterior (GRFx) directions. Two 60-second trials were recorded. On average, 80 (30) strides were analyzed per participant. GRFx was used to compute propulsive impulses produced by the paretic and nonparetic limbs. Propulsive impulses were defined as the force-time integral for anteriorly directed forces.² Symmetry of propulsion during walking (%Propulsion_{walk}) was defined as the percent of the total propulsive

impulse (paretic + nonparetic) produced by the paretic limb.² GRFz was used to compute phase coordination index (PCI_{walk}), as detailed previously.¹³ In brief, we computed the discrete relative phase between limbs (ϕ_i) as the ratio of paretic step time to nonparetic stride time multiplied by 360° (Eq. 1). Step and stride times were computed from the time of paretic and nonparetic heel strikes (tP_i , tNP_i). Values were computed for every i th heel strike. A heel strike was identified every time GRFz exceeded 15 N. As shown in Eq. 2, values for ϕ_i were normalized to 180° . The mean normalized difference from 180° and coefficient of variation of the discrete relative phase were computed. Values were expressed in percent and summed to obtain PCI_{walk} . Consequently, PCI_{walk} provided a composite measure of the accuracy and consistency of interlimb phasing during walking, where 0% would represent a perfectly accurate and consistent antiphase relationship between limbs. Walking data were excluded for one significant outlier whose values were more than 4 SD outside the mean.

$$\phi_i = \frac{tP_i - tNP_i}{tNP(i+1) - tNP_i} \times 360^\circ$$

(Eq. 1)

$$PCI_{walk}(\%) = \left[\frac{\mu(|\phi_i - 180^\circ|)}{180^\circ} \times 100\% \right] + \left[\frac{\sigma(\phi_i)}{\mu(\phi_i)} \times 100\% \right]$$

(Eq. 2)

Work symmetry during pedaling was examined in the stroke group using methods described in prior publications.^{3,11,14,15} In brief, participants were seated on a pedaling device with a solid crank shaft attached to a rigid backboard oriented 40° from horizontal (PowerTower with EMC Ergometric Multi Cycle attachment, Total Gym, San Diego, California). The feet were secured to the pedals. Participants were asked to perform conventional, bilateral coupled pedaling for 2 minutes with an auditory pacing cue at 45 revolutions per minute (RPM). Because work symmetry was calculated during bilateral coupled pedaling, the nonparetic limb was able to compensate for the paretic limb. Forces applied to each pedal were measured with 6-degree of freedom force transducers (Delta 660-60, ATI Industrial Automation, Apex, North Carolina). The position of the crank shaft and the pedals was measured with optical encoders (BEI Model EX116-1024-2, BEI Sensors, Thousand Oaks, California). Torque contributing to angular rotation of the crank shaft (ie, torque tangential to the crank arm) was calculated. Data were referenced to crank shaft position and ensemble averaged. Positive area under the resulting curve represented propulsive work. Percent work done by the paretic limb ($\%Work_{ped}$) was computed as: $Work_{paretic}/Work_{total} \times 100$, where $Work_{paretic}$ was the work done by the paretic limb and $Work_{total}$ was the sum of the work done by both legs. A value of 50% would represent equal sharing of the work between limbs.

Interlimb coordination during pedaling was assessed in stroke and control participants using a custom-designed, split-crank pedaling device that we have described previously.¹¹ Briefly, the device was equipped with a bisected crank shaft that rendered the right and left pedals mechanically uncoupled, allowing each to function independently. An eccentric pulley system was used to mimic the mechanical work performed by the contralateral limb. In a prior setup session, participants performed unilateral pedaling with each leg against up to 6 different elastic resistance loads in the eccentric pulley system. Participants also performed bilateral coupled pedaling on the same apparatus but with the pedals coupled, without the elastic loads, and with a frictional load applied through a centric pulley. The elastic load that best matched the velocity and muscle activation profiles during conventional (bilateral coupled pedaling) and unilateral pedaling was then selected for use during bilateral uncoupled pedaling. The elastic load was individually selected for each leg. Procedures are described in more detail elsewhere.¹¹ During the test session, participants were positioned supine with the feet secured to the pedals. They were asked to pedal forward with both legs simultaneously and maintain an antiphase (180°) relation between the left and right pedals. An auditory pacing cue at 45 RPM was used. After 45

second of exposure, 60 seconds of data were collected. The position of the right and left crank shaft was measured with rotary optical encoders (MR318, Micronor Inc, Newbury Park, California) that carried signals to controller units (MR310, Micronor). Top dead center position (0°) was defined separately for each crank arm as the position where the foot was nearest to the hip and the crank arm was parallel to the floor. Position data were used to compute the phase coordination index for pedaling (PCI_{ped}). As shown in Eq. 3, we computed the continuous relative phase (CRP) of the limbs as the absolute difference between the positions of the right and left crank shafts at every data point. The smallest difference between limb positions was always used. For example, CRP would be 130° if the reference limbs were at 0° and the other was at 130° or 230°. Adapting previous methods,¹³ we calculated the PCI_{ped} from CRP as shown in Eq. 3. PCI_{ped} provided a composite measure of the accuracy (mean normalized difference from 180°) and consistency (coefficient of variation of CRP) of interlimb phasing during pedaling, where 0% would represent a perfectly accurate and consistent antiphase relationship between limbs. Split crank pedaling data from one participant were unavailable due to equipment malfunction.

$$PCI_{ped}(\%) = \left[\frac{\mu(|CRP - 180|)}{180} \times 100\% \right] + \left[\frac{\sigma(CRP)}{\mu(CRP)} \times 100\% \right]$$

(Eq. 3)

Clinical Measures

Stroke-related impairment was assessed using the motor portion of the lower extremity Fugl-Meyer score (FMLE, max score: 34). Self-selected, comfortable walking speed was assessed with the 8-m walk test.

Statistics

Because outcomes were nonnormal and sample sizes were small, nonparametric statistics were used, except when comparing PCI_{walk} values between stroke and control groups. In this instance, independent *t* tests were used because control data were extracted from a report of the measure in 12 healthy controls.¹⁶ %Propulsion and %Work values performed by the paretic limb from walking and pedaling were compared with 50% using 1-sample Wilcoxon signed rank tests. PCI_{ped} was compared between stroke and control groups with Mann-Whitney *U* tests. To compare variances of %Propulsion, %Work and PCI between walking and pedaling, we used a squared-ranks equality of variance test. Relationships between symmetry (%Propulsion, %Work), interlimb coordination (PCI), and clinical measures (FMLE and walking speed) were tested with Spearman's rank correlations. For all ranks, the least positive absolute value was given the lowest rank. For comparative and illustrative purposes, we also present Pearson correlations for these same associations. All statistical tests used SPSS Statistics 22.0f, and $P < 0.05$ was accepted as significant.

Results

Participants with stroke displayed asymmetric propulsion and work output (paretic < nonparetic) and impaired interlimb coordination during walking and pedaling. As shown in Table 2, values for %Propulsion_{walk} and %Work_{ped} in people with stroke were significantly less than 50% (mean difference %Propulsion_{walk}: -21.8%, $Z = -3.3$, $P = 0.001$; mean difference %Work_{ped}: -8.1%, $Z = -3.3$, $P = 0.001$). The stroke group also displayed significantly higher values than controls for PCI_{walk} and PCI_{ped} (mean difference PCI_{walk} : 7.1, $t = 3.3$, $P = 0.002$, mean difference PCI_{ped} : 44.5, $Z = -4.2$, $P < 0.001$).

Table 2. - Symmetry and Interlimb Coordination During Walking and Pedaling^a

<i>Walking</i>			
Propulsion	<i>Paretic</i>	<i>Nonparetic</i>	<i>%Propulsion_{walk}</i>
Propulsive impulse, N·s	4.7 (4.6)	10.8 (4.7)	28.2 (17.5) ^b

Interlimb coordination	<i>Stroke (n=19)</i>	<i>Control (n=12)^c</i>	
PCI _{walk} , %	13.3 (7.3) ^d	6.2 (1.0)	
<i>Pedaling</i>			
Work	<i>Paretic</i>	<i>Nonparetic</i>	<i>%Work_{ped}</i>
Propulsive work, N·m	34 (7)	49 (16)	41.9 (7.6) ^b
Interlimb coordination	<i>Stroke (n=19)</i>	<i>Control (n=15)</i>	
PCI _{ped} , %	76.8 (28.4) ^d	32.3 (10.1)	

Abbreviation: PCI, phase coordination index.

^aValues are mean (SD).

^b $P < 0.05$ compared with 50%.

^cPCI_{walk} values for controls were extracted from a report of the measure in 12 healthy controls from the publication by Meijer et al.¹⁶

^d $P < 0.05$ stroke versus control.

During walking and pedaling, asymmetric output was associated with impaired interlimb coordination. As shown in the main plot of Figure 1A, the Spearman's rank correlations revealed a significant inverse relationship between PCI and %Propulsion during walking ($R^2 = 0.79$, $P < 0.001$) and %Work during pedaling ($R^2 = 0.62$, $P < 0.001$). Significant Pearson correlations between PCI and %Propulsion, %Work were also evident as displayed in the inset of Figure 1A. The inset also reveals a larger range of values for %Propulsion during walking (0%-51%) than for %Work during pedaling (30%-54%) ($Z = 2.6$, $P = 0.005$) and a larger range of values for PCI during pedaling (31%-114%) than walking (5%-33%) ($Z = 3.6$, $P = 0.003$).

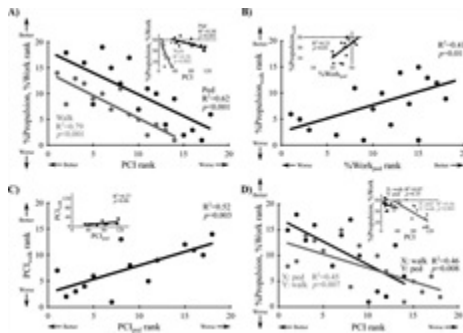


Figure 1: Associations between work symmetry and interlimb coordination. (A) Associations between symmetry (%Propulsion, %Work) and interlimb coordination (PCI) are shown for walking and pedaling tasks. Associations between walking versus pedaling are shown for (B) symmetry (%Propulsion, %Work) and (C) interlimb coordination (PCI). (D) Associations between symmetry (%Propulsion, %Work) and interlimb coordination (PCI) are shown when one variable was measured during walking and the other was measured during pedaling. Large plots show rank (nonparametric) associations, while insets show raw value (parametric) associations. For all ranks, the least positive absolute value was given the lowest rank. Lower ranks for %Propulsion and %Work represent worse symmetry; lower ranks for PCI represent better interlimb coordination. Arrows are displayed on each axis to indicate whether values are better or worse for the respective variable. Data points represent individual participants. Lines of best fit, R^2 values, and P values are displayed for each association. PCI, phase coordination index.

Asymmetry and impaired interlimb coordination during pedaling were associated with the same impairments in walking. As shown in Figures 1B and 1C, Spearman's rank correlations revealed significant positive relationships between %Work during pedaling and %Propulsion during walking ($R^2 = 0.41$, $P = 0.01$) and PCI during pedaling

and walking ($R^2 = 0.52$, $P = 0.003$). The insets reveal the same trends for Pearson correlations (%Propulsion, %Work: $R^2 = 0.33$, $P = 0.03$, PCI: $R^2 = 0.27$, $P = 0.06$).

Given the significant associations between measures and tasks, we performed a post hoc examination of the correlations between %Propulsion, %Work and PCI across tasks. Results indicate that better interlimb coordination was associated with better symmetry, even when the 2 variables were measured during different tasks. As shown in Figure 1D, the Spearman's rank correlations revealed a significant inverse relationship between %Propulsion_{walk} and PCI_{ped} ($R^2 = 0.45$, $P = 0.007$) and between %Work_{ped} and PCI_{walk} ($R^2 = 0.46$, $P = 0.008$). The Pearson correlations shown in the inset support the rank data for PCI_{ped} versus %Propulsion_{walk} ($R^2 = 0.56$, $P = 0.001$), but not for PCI_{walk} versus %Work_{ped} ($R^2 = 0.07$, $P = 0.35$).

Regardless of task, asymmetry and interlimb coordination were associated with stroke-related motor impairment as measured by FMLE but not walking speed. As shown in Figures 2A and 2B, there was a significant positive relationship between FMLE and %Propulsion, %Work (walk: $R^2 = 0.48$, $P = 0.004$; pedal: $R^2 = 0.56$, $P < 0.001$) and a significant inverse relationship between FMLE and PCI (walk: $R^2 = 0.52$, $P = 0.004$; pedal: $R^2 = 0.67$, $P < 0.001$). Neither %Propulsion, %Work nor PCI during pedaling or walking was significantly associated with walking speed ($R^2 \leq 0.22$, $P \geq 0.05$). See Figures 2C and 2D.

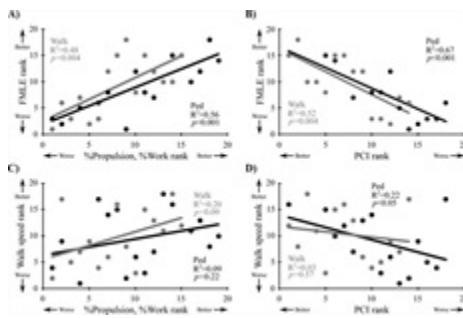


Figure 2.: Associations of work symmetry and interlimb coordination with clinical assessments. For both walking and pedaling, rank (nonparametric) associations are shown for Fugl-Meyer lower extremity motor score (FMLE) with (A) symmetry (%Propulsion, %Work) and (B) interlimb coordination (PCI) and for walking speed with (C) symmetry (%Propulsion, %Work) and (D) interlimb coordination (PCI). For all ranks, the least positive absolute value was given the lowest rank. Lower ranks for %Propulsion and %Work represent worse symmetry; lower ranks for PCI represent better interlimb coordination; lower ranks for FMLE represent worse motor impairment; lower ranks for walking speed represent slower walking. Arrows are displayed on each axis to indicate whether values are better or worse for the respective variable. Data points represent individual participants. Lines of best fit, R^2 values, and P values are displayed for each association. PCI, phase coordination index.

Asymmetry and impaired interlimb coordination during pedaling were associated with the same impairments in walking. As shown in Figures 1B and 1C, Spearman's rank correlations revealed significant positive relationships between %Work during pedaling and %Propulsion during walking ($R^2 = 0.41$, $P = 0.01$) and PCI during pedaling and walking ($R^2 = 0.52$, $P = 0.003$). The insets reveal the same trends for Pearson correlations (%Propulsion, %Work: $R^2 = 0.33$, $P = 0.03$, PCI: $R^2 = 0.27$, $P = 0.06$).

Given the significant associations between measures and tasks, we performed a post hoc examination of the correlations between %Propulsion, %Work and PCI across tasks. Results indicate that better interlimb coordination was associated with better symmetry, even when the 2 variables were measured during different tasks. As shown in Figure 1D, the Spearman's rank correlations revealed a significant inverse relationship between %Propulsion_{walk} and PCI_{ped} ($R^2 = 0.45$, $P = 0.007$) and between %Work_{ped} and PCI_{walk} ($R^2 = 0.46$, $P =$

0.008). The Pearson correlations shown in the inset support the rank data for PCI_{ped} versus $\%Propulsion_{walk}$ ($R^2 = 0.56$, $P = 0.001$), but not for PCI_{walk} versus $\%Work_{ped}$ ($R^2 = 0.07$, $P = 0.35$).

Regardless of task, asymmetry and interlimb coordination were associated with stroke-related motor impairment as measured by FMLE but not walking speed. As shown in Figures 2A and 2B, there was a significant positive relationship between FMLE and $\%Propulsion$, $\%Work$ (walk: $R^2 = 0.48$, $P = 0.004$; pedal: $R^2 = 0.56$, $P < 0.001$) and a significant inverse relationship between FMLE and PCI (walk: $R^2 = 0.52$, $P = 0.004$; pedal: $R^2 = 0.67$, $P < 0.001$). Neither $\%Propulsion$, $\%Work$ nor PCI during pedaling or walking was significantly associated with walking speed ($R^2 \leq 0.22$, $P \geq 0.05$). See Figures 2C and 2D.

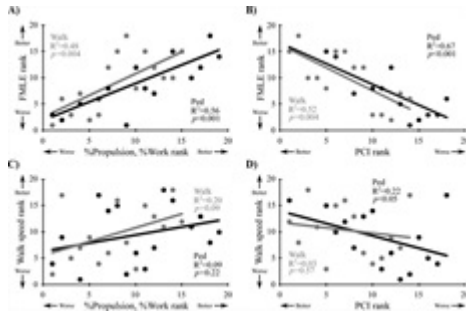


Figure 2.:

Associations of work symmetry and interlimb coordination with clinical assessments. For both walking and pedaling, rank (nonparametric) associations are shown for Fugl-Meyer lower extremity motor score (FMLE) with (A) symmetry ($\%Propulsion$, $\%Work$) and (B) interlimb coordination (PCI) and for walking speed with (C) symmetry ($\%Propulsion$, $\%Work$) and (D) interlimb coordination (PCI). For all ranks, the least positive absolute value was given the lowest rank. Lower ranks for $\%Propulsion$ and $\%Work$ represent worse symmetry; lower ranks for PCI represent better interlimb coordination; lower ranks for FMLE represent worse motor impairment; lower ranks for walking speed represent slower walking. Arrows are displayed on each axis to indicate whether values are better or worse for the respective variable. Data points represent individual participants. Lines of best fit, R^2 values, and P values are displayed for each association. PCI, phase coordination index.

DISCUSSION

This study found that asymmetry and impaired interlimb coordination are associated during pedaling and walking. Measures of work symmetry and interlimb coordination obtained in pedaling (bilateral coupled and uncoupled) are related to analogous measures in walking. These findings suggest that impaired interlimb coordination contributes to asymmetry in walking, as it does in pedaling, and pedaling may provide useful insights about walking. Asymmetry and impaired interlimb coordination measured from walking and pedaling were associated with lower limb motor impairment. Hence, these measures may have important rehabilitative implications. We also found that bilateral uncoupled pedaling is more sensitive to interlimb coordination deficits, while walking is more sensitive to asymmetry. Compared to walking, bilateral uncoupled pedaling prevents compensation, compels muscle activity in the paretic limb, and exposes interlimb phasing deficits. This task may have a therapeutic value for improving paretic motor output and retraining interlimb coordination.

This study sought to explain the persistence of propulsive asymmetry during walking in people with chronic stroke.^{1,2,17} This effort was motivated by a previous report from our laboratory, which found that work asymmetry during pedaling was more strongly associated with abnormal interlimb coordination than impaired motor output of the paretic limb.¹¹ In the current report, we found that individuals with stroke with the most asymmetric propulsive output also had the greatest impairment in interlimb coordination during walking. These data provide evidence that the phenomena observed in pedaling extend to walking. Although not causative, our

results suggest that, as postulated in our previous report, propulsive asymmetry may occur to allow sufficient locomotor performance despite impairments in interlimb coordination. Future work should address causality.

Pedaling is a useful model of functional lower limb movement because it involves continuous, reciprocal, multijoint movement of both limbs; it can be done in supine or sitting positions, eliminating the need for body weight support; and it enables unique manipulations, such as a comparison between unilateral and bilateral uncoupled tasks. However, the existence of these motor behaviors in pedaling does not establish their existence or importance in walking. The present study was needed to determine whether observations in pedaling extend to walking and whether pedaling provides useful information about asymmetry during walking. Our results suggest that pedaling (bilateral coupled and uncoupled) provides useful information about walking impairment. Work asymmetry and interlimb coordination during pedaling were strongly associated with analogous measures in walking. Interestingly, Bowden et al² reported a similar association as seen in this study ($R^2 = 0.38$ vs $R^2 = 0.33$ in the current study) between propulsive impulse during walking and positive work during bilateral coupled pedaling. In the current study we even found significant associations between PCI_{ped} and $\%Propulsion_{walk}$ and between $\%Work_{ped}$ and PCI_{walk} . Hence, these behaviors are unlikely to be independent phenomena and probably represent stroke-related impairments that manifest across tasks.

Another novel finding from this study is that pedaling and walking provide distinct and complementary insights into lower limb motor impairment after stroke. Post hoc exploratory analysis showed larger interindividual variation in PCI during bilateral uncoupled pedaling than walking and larger interindividual variation in $\%Propulsion$ during walking than $\%Work$ during bilateral coupled pedaling. These observations suggest that bilateral uncoupled pedaling is more sensitive than walking to interlimb phasing deficits, and walking exposes asymmetry more effectively than pedaling. The demands of each task are different because the feet are secured to pedals and constrained to a circular trajectory during pedaling, while the feet are free during walking. To perform bilateral uncoupled pedaling, each limb must produce muscle activity across multiple joints that is appropriately timed and of sufficient amplitude to rotate a crank shaft in a coordinated fashion with respect to the contralateral limb. Thus, bilateral uncoupled pedaling compels paretic limb use (resulting in decreased interindividual variation in $\%Work$) and exposes problems with interlimb coordination (resulting in increased interindividual variation in PCI).

During walking, many strategies can advance the paretic limb for swing (eg, hip hiking and vaulting) and stabilize it during stance (eg, knee hyperextension) with little or no activation of the muscles controlling the paretic hip, knee, or ankle.¹⁸ In other words, walking can be achieved through compensatory strategies that demand little propulsion from the paretic limb. Furthermore, because walking is performed over a narrow base of support, errors in interlimb coordination can result in falls.¹⁹ These consequences disincentivize paretic limb use and may result in the paretic limb contributing less propulsion than it is capable of to avoid issues with interlimb coordination and falls (resulting in increased interindividual variation in $\%Propulsion$). Our pedaling data support this framework. During bilateral coupled pedaling, work output is more symmetric than propulsive output in walking. People with stroke are also capable of unilateral pedaling even when they display substantial work asymmetry and little use of their paretic limb during conventional bilateral pedaling.¹¹

From a clinical perspective, we found that asymmetry and impaired interlimb coordination during walking and pedaling were associated with FMLE scores but not walking speed. The FMLE score quantifies motor impairments of the paretic limb, such as abnormal reflex excitability and synergistic movements, that are direct consequences of stroke.²⁰ While affected by these impairments, walking speed is a functional measure that is also influenced by the extent to which individuals with stroke compensate for these impairments.²¹ Hence, $\%Propulsion$, $\%Work$, and PCI are more reflective of the direct effects of stroke than the extent to which stroke survivors mitigate those effects through compensatory movement patterns. These results also suggest that to enhance recovery from stroke, interventions should disallow compensation, expose impairment, and provide

opportunities to reduce it. Like constraint-induced movement therapy in the upper limb,²² bilateral uncoupled pedaling may provide such an opportunity for the lower limbs. The uncoupled nature of the task compels muscle activation of the paretic limb and provides an opportunity to retrain the typical 180° phasing between limbs. Given that the feet are fixed and constrained to a circular trajectory, a limited set of muscle activation patterns can rotate the crank. Thus, repeated exposure to uncoupled pedaling may improve the timing and amplitude of paretic muscle activity, improve interlimb coordination, and reduce asymmetric work output. We are in the process of developing such an intervention and testing its effects. If successful, future work will examine its effects on walking, where the demands for balance and body weight support make compensation and asymmetry more attractive than in pedaling.

Study Limitations

An important limitation of this study is the use of nonparametric statistics, which inflate type I error. A nonparametric approach was necessary because our data were not normally distributed. However, we also used parametric statistics in our post hoc analysis of the nonranked data. In most cases, the parametric approach yielded the same results as the ranked tests, which improves our confidence in our conclusion result. Nevertheless, future work involving larger, more normally distributed samples is warranted. Workloads were not quantified during bilateral uncoupled pedaling, and the elastic loads used during this condition presented discrete, not continuous, levels of resistance. Consequently, there may have been differences in the workload produced by the paretic limb during conventional (bilateral coupled pedaling) and bilateral uncoupled pedaling. These differences could cause phase disruptions that influence interlimb coordination. Moreover, these phase disruptions and the impact on interlimb coordination may vary based upon the degree of workload mismatch between conditions for each individual participant. This issue limits insights into interlimb coordination during pedaling and its association with other outcome measures, particularly work symmetry during pedaling.

CONCLUSIONS

Impaired interlimb coordination may contribute to propulsive asymmetry in walking, similar to what is seen in pedaling. Pedaling provides useful insights into stroke-related motor impairments in walking, but walking and pedaling also provide distinct information about stroke-related movement impairments of the lower limbs. Differences are likely explained by the extent to which each task allows compensation (walking > pedaling) or compels use of the paretic limb (pedaling > walking). Bilateral uncoupled pedaling may be a useful rehabilitation tool.

ACKNOWLEDGMENTS

The authors would like to thank Christine Smith, Amanda Waldera, and Ben Rappaport for their help with pilot work, Tom Ruopp for technical assistance with the pedaling device, and Tim Boerger for technical assistance with the split-belt treadmill.

REFERENCES

1. Olney SJ, Griffin MP, Monga TN, McBride ID. Work and power in gait of stroke patients. *Arch Phys Med Rehabil*. 1991;72(5):309–314.
4. Chen HY, Chen SC, Chen JJ, Fu LL, Wang YL. Kinesiological and kinematical analysis for stroke subjects with asymmetrical cycling movement patterns. *J Electromyogr Kinesiol*. 2005;15(6):587–595. doi:10.1016/j.jelekin.2005.06.001.
5. Promjunyakul NO, Schmit BD, Schindler-Ivens SM. A novel fMRI paradigm suggests that pedaling-related brain activation is altered after stroke. *Front Hum Neurosci*. 2015;9:324. doi:10.3389/fnhum.2015.00324.

6. Bohannon RW, Larkin PA. Lower extremity weight bearing under various standing conditions in independently ambulatory patients with hemiparesis. *Phys Ther.* 1985;65(9):1323–1325.
7. Clark DJ, Neptune RR, Behrman AL, Kautz SA. Locomotor adaptability task promotes intense and task-appropriate output from the paretic leg during walking. *Arch Phys Med Rehabil.* 2016;97(3):493–496. doi:10.1016/j.apmr.2015.10.081.
8. 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.* 2016;30(8):743–752. doi:10.1177/1545968315624780.
9. Brown DA, Kautz SA, Dairaghi CA. Muscle activity adapts to anti-gravity posture during pedalling in persons with post-stroke hemiplegia. *Brain.* 1997;120(pt 5):825–837.
10. Brown DA, Kautz SA. Increased workload enhances force output during pedaling exercise in persons with poststroke hemiplegia. *Stroke.* 1998;29(3):598–606.
11. Cleland BT, Gelting T, Arand B, Struhar J, Schindler-Ivens S. Impaired interlimb coordination is related to asymmetries during pedaling after stroke. *Clin Neurophysiol.* 2019;130:1474–1487.
12. Swinnen SP, Duysens J. *Neuro-behavioral Determinants of Interlimb Coordination: A Multidisciplinary Approach.* Kluwer Academic; 2004:329.
13. Plotnik M, Giladi N, Hausdorff JM. A new measure for quantifying the bilateral coordination of human gait: effects of aging and Parkinson's disease. *Exp Brain Res.* 2007;181(4):561–570. doi:10.1007/s00221-007-0955-7.
14. Schindler-Ivens S, Brown DA, Lewis GN, Nielsen JB, Ondishko KL, Wieser J. Soleus H-reflex excitability during pedaling post-stroke. *Exp Brain Res.* 2008;188(3):465–474. doi:10.1007/s00221-008-1373-1.
15. Fuchs DP, Sanghvi N, Wieser J, Schindler-Ivens S. Pedaling alters the excitability and modulation of vastus medialis H-reflexes after stroke. *Clin Neurophysiol.* 2011;122(10):2036–2043. doi:10.1016/j.clinph.2011.03.010.
16. Meijer R, Plotnik M, Zwaafink EG, et al. Markedly impaired bilateral coordination of gait in post-stroke patients: Is this deficit distinct from asymmetry? A cohort study. *J Neuroeng Rehabil.* 2011;8:23. doi:10.1186/1743-0003-8-23.
17. Turns LJ, Neptune RR, Kautz SA. Relationships between muscle activity and anteroposterior ground reaction forces in hemiparetic walking. *Arch Phys Med Rehabil.* 2007;88(9):1127–1135. doi:10.1016/j.apmr.2007.05.027.
18. Knutsson E, Richards C. Different types of disturbed motor control in gait of hemiparetic patients. *Brain.* 1979;102(2):405–430.
19. Sousa AS, Tavares JM. Interlimb coordination during step-to-step transition and gait performance. *J Mot Behav.* 2015;47(6):563–574. doi:10.1080/00222895.2015.1023391.
20. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. *Scand J Rehabil Med.* 1975;7(1):13–31.
21. Levin MF, Kleim JA, Wolf SL. What do motor “recovery” and “compensation” mean in patients following stroke? *Neurorehabil Neural Repair.* 2009;23(4):313–319. doi:10.1177/1545968308328727.
22. Taub E, Uswatte G, Pidikiti R. Constraint-induced movement therapy: a new family of techniques with broad application to physical rehabilitation—a clinical review. *J Rehabil Res Dev.* 1999;36(3):237–251.

Keywords:

locomotion; stroke; stroke rehabilitation

Supplemental Digital Content

- JNPT_2021_08_20_CLELAND_2100043_SDC1.mp4; [Video] (72.43 MB)

