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ORIGINAL ARTICLE

Relationship Between Shoulder Pain and Kinetic and Temporal-Spatial Variability in Wheelchair Users

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Abstract

Objective: To examine intra-individual variability of kinetic and temporal-spatial parameters of wheelchair propulsion as a function of shoulder pain in manual wheelchair users (MWUs).

Design: Cohort.

Setting: University research laboratory.

Participants: Adults with physical disabilities (N=26) who use a manual wheelchair for mobility full time (>80% ambulation).

Interventions: Participants propelled their own wheelchairs with force-sensing wheels at a steady-state pace on a dynamometer at 3 speeds (self-selected, 0.7m/s, 1.1m/s) for 3 minutes. Temporal-spatial and kinetic data were recorded unilaterally at the hand rim.

Main Outcome Measures: Shoulder pain was quantified with the Wheelchair Users Shoulder Pain Index. Intra-individual mean, SD, and coefficient of variation (CV=mean/SD) with kinetic and temporal-spatial metrics were determined at the handrim.

Results: There were no differences in mean kinetic and temporal-spatial metrics as a function of pain group (*P* values >.016). However, individuals with pain displayed less relative variability (CV) in peak resultant force and push time than pain-free individuals (*P*<.016).

Conclusions: Shoulder pain had no influence on mean kinetic and temporal-spatial propulsion variables at the handrim; however, group differences were found in relative variability. These results suggest that intra-individual variability analysis is sensitive to pain. We propose that variability analysis may offer an approach for earlier identification of MWUs at risk for developing shoulder pain.

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There are an estimated 2 million manual wheelchair users (MWUs) in the United States.[1] Although manual wheelchair propulsion offers numerous benefits, it is often associated with upper extremity pain and injury that can severely impact function and independence.[2-4] Because of the adverse consequences of upper extremity pain in MWUs, a large amount of research has focused on determining factors related to upper extremity pain. For instance, propulsion parameters including contact angle, stroke frequency, and rate of rise and magnitude of peak forces and moments,[2-8] as well as demographic features such as years of wheelchair use, sex, weight, functional injury level, and age, have been investigated.[5,9-12]

Although the shoulder's vulnerability to propulsion has been well established, researchers have not found clear distinctions between the technique of MWUs with and without shoulder pain.[7,8] While larger forces and moments have been related to measures of shoulder pathology, it remains unclear how pain affects biomechanics at the handrim. Historically, propulsion biomechanics research related to upper limb pain and injury has focused almost entirely on the average kinetic and temporal-spatial metrics.[7,8]

There is increasing evidence that variations in movement within an individual provide valuable information concerning underlying motor control and pathology.[13,14] It is maintained that movement variability within limits is a normal characteristic of healthy neuromotor systems and affords greater adaptability to environmental stressors.[14,15] Variability outside the normal range is indicative of

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pathology, and individuals experiencing pain are known to have distinct variability profiles during various motor tasks.[14,16] For example a relation between kinematic and temporal variability and skeletal injury has been demonstrated in ambulatory individuals with knee,[17] shoulder,[18] and low back pain.[19] In all of these cases, individuals with pain demonstrated less variability than their healthy peers. It has been suggested that decreased motor variability results in the development of musculoskeletal disorders and injury.[14,20]

To our knowledge, this is the first published investigation of variability in wheelchair propulsion at the handrim as a function of shoulder pain. The study of movement variation during wheelchair propulsion may have practical implications both clinically and scientifically because it is a parameter that is easily captured with an instrumented wheel and may be modifiable through a combination of technique training or wheelchair configuration.

The purpose of this study was to determine whether there are differences in intra-individual (eg, within the individual) variability in kinetic and timing propulsion parameters as a function of shoulder pain in full-time MWUs. Based on the extant literature, we predicted that MWUs with shoulder pain would demonstrate less kinetic and temporal-spatial variability at the handrim during propulsion compared with those without pain.

Methods

Participants

Twenty-six individuals (10 women, 16 men) from the Urbana-Champaign community volunteered and provided informed consent before participation in this study. All the participants were MWUs who used a wheelchair as their primary means of ambulation for more than 1 year and were between 18 and 64 years of age. People were excluded from participation if they had upper limb pain that prohibited them from propelling a manual wheelchair. The wheelchair users' diagnoses include spinal cord injury (T8 and below, n=12), spina bifida (n=8), cerebral palsy (n=1), spinal cyst (n=2), arthrogryposis (n=1), and amputation (n=2). Participants were separated into a pain group or a no-pain group based on self-report of shoulder pain. They were asked whether they were currently experiencing shoulder pain, and rated their current level of shoulder pain with a 10-cm visual analog scale[21] of 0 (no pain) to 10 (high pain).

Protocol

All experimentation was approved by the local institutional review board. On arrival to the laboratory, participants received an explanation of the experimental procedures and were provided the opportunity to ask questions. After all questions were answered, participants were asked to provide informed consent. They then provided demographic information and completed the Wheelchair Users Shoulder Pain Index (WUSPI) (table 1).

List of abbreviations:

CV	**coefficient of variation**
MWU	**manual wheelchair user**
RPE	**rating of perceived exertion**
WUSPI	**Wheelchair Users Shoulder Pain Index**

Data collection

Participants' own wheelchairs were fitted bilaterally with 25-in-diameter SmartWheels[22,23,a] and placed on a single drum dynamometer with a fly wheel and tie-down system. The participants were asked to propel at constant speeds of 1.1m/s (fast) and 0.7m/s (slow) and at a self-selected speed for 3 minutes. Perceived exertion was quantified after each trial with the Borg perceived exertion scale. Full rest and recovery were provided between trials. The sequence of speeds was randomly selected for each subject, and a speedometer placed in front of each participant was used to provide real-time visual feedback during propulsion. In addition, subjects were given time to acclimate to the dynamometer and propulsion speed before each trial.

Kinetic and temporal-spatial data were collected and streamed wirelessly from the right-side SmartWheel for each trial at 100Hz once a steady-state velocity was reached. A push cycle was defined as the period when the moment applied to the handrim was more than 0.8Nm for more than 150 milliseconds.

The WUSPI, a reliable and valid 15-item questionnaire, was used to quantify the presence of pain in all participants.[24,25] It measures how shoulder pain has interfered with daily activities, such as transferring, wheeling, and self-care. Each item is scored from 0 to 10, with 10 representing shoulder pain that has completely interfered with the activity during the past week. Adding the scores for each item answered derives the total score. Total scores range from 0 (no pain) to 150 (maximum limitations caused by pain).

Ratings of perceived exertion (RPEs) were recorded immediately after each propulsion trial using the Borg scale as an index of perceived physiological stress.[26] All participants received detailed instructions about the use of the scale and were given examples of how they might rate differentiated RPE.

Data reduction

Peak resultant force, peak rate of rise of resultant force (N/s), contact angle (degrees), stroke frequency (strokes/s), and push time (s) were calculated with a custom MATLAB[b] program for each trial. Peak resultant force is the maximum total force applied to the handrim per stroke cycle, while peak rate of rise of resultant force is the maximum instantaneous loading rate at the handrim.[5,22,27] These variables were selected because of their association with the development of upper extremity pain and injury.[2,5,6]

All propulsion outcome measures were formulated as mean ($\overline{X}$), intra-individual SD, and coefficient of variation (CV). Figure 1 illustrates the peak resultant force at the handrim over

Table 1 Demographic characteristics

Characteristics	Pain	No Pain
Subjects	13	13
Age (y)	28.5±12.3	20.9±4.9
Sex (M/F)	8/5	8/5
Weight (kg)	73.8±25.2	62.8±14.3
Wheelchair use (y)	15.3±11.4	12.9±5.3
WUSPI score	22.3±21.4*	3.9±5.0

NOTE. Values are n or mean ± SD.
Abbreviations: F, female; M, male.
* Significant difference, between groups (pain/no pain) (P<.012).

3 minutes of propulsion at fast speed in a representative participant without shoulder pain. It is clear in the figure that there are slight fluctuations in peak resultant force and timing of each push. This push-to-push variation within an individual was quantified with SD (absolute amount of variation) and CV (relative variation) (see fig 1).

Statistical analysis

Statistical analyses were conducted using SPSS version 21 for Windows.[c] All data were examined for normality; appropriate statistical analyses were then used as needed. Differences in demographic characteristics were compared between groups. Continuous independent variables (age, years of wheelchair use, weight, WUSPI score) were compared using a Student *t* test with a Bonferroni correction ($P=.0125$). The mean, SD, and CV of the dependent variables (peak resultant force, peak rate of rise of resultant force, contact angle, stroke frequency, push time) were compared using a 2-by-3 mixed-model multivariate analysis of variance with the between-subject factor of group (pain/no pain) and the within-subject factor of speed (slow, self-select, fast). Significance was set to .016 (.05/3) based on the inclusion of mean, SD, and CV into the multivariate analysis of variance. A Bonferroni post hoc test was applied to further analyze significant main effects where appropriate.

Results

Participant demographics

The pain group had a higher total WUSPI score than the no-pain group ($P=.006$) (see table 1).

Velocity and perceived exertion

All participants maintained speeds very close to the targets provided in real time. Actual propulsion speed differences between groups (pain/no pain) were not significantly different ($P>.05$). Perceived exertion scores were low (20%−30% effort) for all speed conditions and not significantly different between groups ($P>.05$). On average, the magnitude of self-selected speeds fell in between the slow and fast conditions for both groups (table 2).

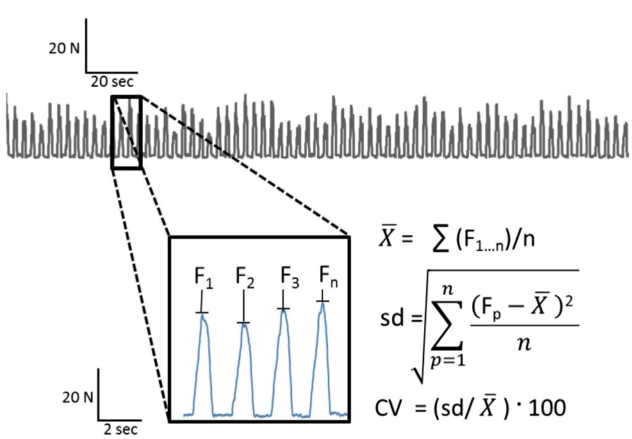

Fig 1 Representative peak force data and derivation of propulsion outcome variables. Abbreviations: F, force; sd, standard deviation; $\bar{X}$,mean.

Kinetic and temporal-spatial propulsion outcomes

Multivariate report

The mixed-design multivariate analysis of variance showed a main effect for pain (Pillai-Bartlett trace=.376, $F_{15,61}=2.15$, $P=.01$, $\eta^2=.34$) and speed (Pillai-Bartlett trace=.828, $F_{30,124}=2.91$, $P<.001$, $\eta^2=.41$).

Average kinetic and temporal-spatial metrics

Replicating previous work, average kinetic and temporal-spatial performance variables did not differ between those with and without pain ($P>.016$) (table 3). As expected, stroke frequency increased with faster propulsion speeds, while push time decreased ([$F_{2,75}=9.8$, $P<.001$, $\eta^2=.29$] and [$F_{2,75}=23.2$, $P<.001$, $\eta^2=.383$], respectively) (table 4).

Absolute intravariation (SD) propulsion variables

Absolute intra-SD in peak resultant force was significantly different between pain groups, with those with pain being less variable ($F_{1,75}=7.5$, $P=.007$, $\eta^2=.092$) (see table 3). Statistically significant differences in absolute SD were also found based on speed condition ($P<.016$). Push time became less variable with speed, while stroke frequency became more variable ([$F_{2,75}=22.8$, $P<.001$, $\eta^2=.379$] and [$F_{2,75}=4.7$, $P=.01$, $\eta^2=.11$], respectively) (see table 4).

Relative intravariation (CV) propulsion variables

CV (%) was statistically significant as a function of pain group and speed condition (fig 2; see tables 3 and 4). For example, individuals who reported pain displayed a reduced CV compared with those without pain in overall push time, peak resultant force, and contact angle (approaching significance) ([$F_{1,75}=7.4$, $P=.008$, $\eta^2=.09$], [$F_{1,75}=18.0$, $P<.001$, $\eta^2=.19$], and [$F_{1,75}=5.6$, $P=.02$, $\eta^2=.06$], respectively) (see fig 2, see table 3). All participants, regardless of pain status, displayed decreased CV with increased speed for stroke frequency, push time (approaching significance), and peak rate of rise of resultant force (approaching significance) ([$F_{2,75}=12.8$, $P<.001$, $\eta^2=.25$], [$F_{2,75}=4.1$, $P=.02$, $\eta^2=.09$], and [$F_{1,75}=4.2$, $P=.017$, $\eta^2=.10$], respectively) (see table 4).

Discussion

We hypothesized that MWUs experiencing pain would propel with less variable kinetic and temporal-spatial propulsion outcome measures than those without pain. Consistent with our hypothesis, MWUs with pain displayed decreased CV in kinetic and temporal-spatial variables (see table 3). These results provide preliminary evidence that CV may serve as a unique marker of shoulder pain.

Table 2 Actual speeds with corresponding perceived exertion

	Group			
	Pain		No Pain	
Speed Condition	Actual Speed (m/s)	Borg	Actual Speed (m/s)	Borg
Slow (0.7m/s)	0.72±.03	7.8±2.5	0.72±.03	7.6±2.0
Self-selected	0.92±.14	7.9±2.3	0.93±0.23	8.1±1.8
Fast (1.1m/s)	1.12±.04	8.0±1.9	1.14±0.05	8.6±2.4

NOTE. Values are mean ± SD.

Table 3 Performance variables as function of pain status across speed conditions

Performance Variables	Mean		SD		CV	
	Pain	No Pain	Pain	No Pain	Pain	No Pain
Peak Fr (N)	62.6±3.1	61.4±3.0	5.7±0.3*	7.0±0.3*	9.2±0.4*	11.9±0.4*
Peak ror Fr (N/s)	590.5±58.8	587.2±56.7	112.4±9.1	136.2±8.8	22.9±1.3	24.5±1.3
CA (deg)	103.1±3.1	97.3±3.0	5.3±0.2	5.9±0.2	5.2±0.3†	6.5±0.3†
SF (strokes/s)	0.7±.02	0.7±.02	0.1±.003	0.1±.003	17.2±0.3	17.0±0.3
PT (s)	0.6±.02	0.5±.02	0.04±.002	0.04±.002	6.3±0.3*	7.5±0.3*

NOTE. Values are mean ± SE, collapsed for speed (slow, self-selected, fast). Mean, traditional "mean" performance variable; SD, within-subject SD (σ); CV, expressed as % (σ/μ * 100).
Abbrevations: CA, contact angle; Fr, resultant force; PT, push time; ror Fr, rate of rise of resultant force; SF, stroke frequency.
* Significant difference between groups (pain/no pain) ($P<.016$).
† Approaching significance between groups (pain/no pain) ($P<.05$).

In the present study, persons reporting pain displayed reduced relative variability (CV) in both temporal-spatial and kinetic propulsion metrics; however, no differences were observed based on average values. Furthermore, differences in CV based on pain were noted across all speeds, including those self-selected. Specifically, individuals with pain displayed reduced variability in peak resultant force production and time spent in propulsion. Although novel to wheelchair propulsion research, these observations are consistent with several reports[14,20] of movement tasks in which a variety of long-term pain conditions have been associated with reduced motor variability.

Because the current study is cross-sectional, it is not possible to suggest a definitive directional association between peak force variability and shoulder pain; however, 2 possible explanations warrant discussion. It is possible that the presence of shoulder pain in our subjects caused them to constrain their movements to avoid pain, resulting in reduced peak force variability. Alternatively, it is possible that reduced variability is a sign of an underlying mechanism that led to the development of pain by demanding relatively constant loading at the handrim.

The variability overuse hypothesis maintains that a lack of variation results in insufficient time to adapt or heal.[16] If movements are repeated without variation, it is believed that the same soft tissues receive large doses of damaging force application. Increased movement variability would therefore modify tissue loads from repetition to repetition, distribute stresses more equally among tissues, and thus reduce the cumulative load on any particular tissue. In fact, more variable motor strategies have been proposed and supported as a protective factor against the development of work-related musculoskeletal disorders.[18,28] The most frequently suggested intervention against musculoskeletal disorders caused by repetitive work is to decrease its similarity—that is, create more "variation" in biomechanical exposure.[29] Importantly, wheelchair propulsion, with a stroke occurring approximately once per second,[30] far exceeds what most studies consider a repetitive task.[31,32]

The average kinetic and temporal-spatial propulsion outcome measures obtained in the present study are fully consistent with the extant wheelchair propulsion literature.[2,5,7,8] Specifically, the average values observed here were not only comparable in magnitude but similar in the sense that there were no observable differences between the average kinetic and temporal-spatial values of MWUs with and without pain. In fact, previous studies[7,8] have found that pain did not alter the way a person propels a wheelchair. The authors suggested that propulsion biomechanics contribute to pathology, rather than pain or pathology influencing propulsion style.[7,8] While it is difficult to make direct comparisons to this work because of methodological differences, our findings provide preliminary evidence that differences in kinetic and temporal-spatial outcome measures may exist when an intra-individual variability analysis approach is instituted.

Statistically significant relationships were found in outcome measures based on changes in propulsion speed. For example, our

Table 4 Performance variables as a function of speed across pain groups

Performance Variables	Mean			SD			CV		
	Slow	SS	Fast	Slow	SS	Fast	Slow	SS	Fast
Peak Fr (N)	56.2±3.7	62.2±3.7	67.5±3.7	5.8±0.4	6.5±0.4	6.8±0.4	10.6±0.5	10.8±0.5	10.3±0.5
Peak ror Fr (N/s)	482.4±70.8	600.1±70.8	683.1±70.8	118.2±11.0	122.2±11.0	132.6±11.0	27.5±1.6*	22.6±1.6*	21.0±1.6*
CA (deg)	99.7±3.8	99.2±3.8	101.6±3.8	6.1±0.3	5.5±0.3	5.3±0.3	6.5±0.4	5.8±0.4	5.3±0.4
SF (strokes/s)	0.6±.03†	0.7±.03†	0.8±.03†	0.11±.004†	0.12±.004†	0.13±.004†	18.4±0.3†	17.2±0.3†	15.7±0.3†
PT (s)	0.7±.02†	0.5±.02†	0.4±.02†	0.05±.003†	0.04±.003†	0.03±.003†	7.7±0.3*	6.7±0.3*	6.2±0.3*

NOTE. Values are mean ± SE, collapsed for speed (slow, self-selected, fast). Mean, traditional "mean" performance variable; SD, within-subject SD (σ); CV, expressed as % (σ/μ * 100).
Abbrevations: CA, contact angle; Fr, resultant force; PT, push time; ror Fr, rate of rise of resultant force; SF, stroke frequency; SS, self-selected.
* Approaching significance based on the main effect of speed ($P<.05$).
† Significant difference based on the main effect of speed ($P<.016$).

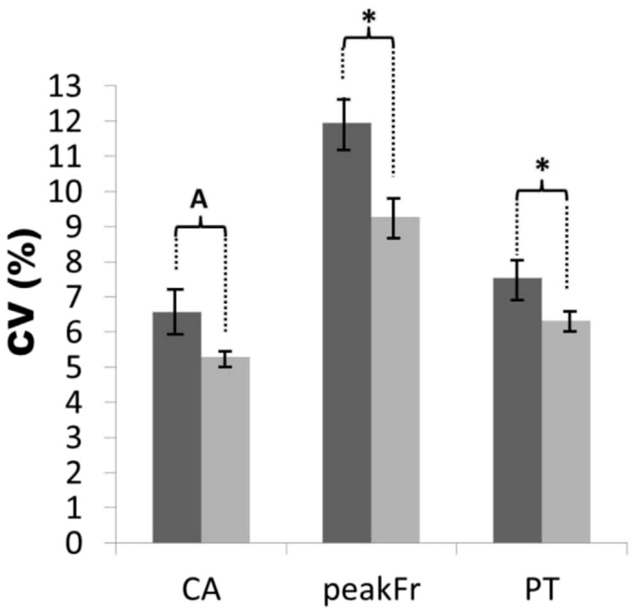

Fig 2 CV group differences. *Significant difference between groups (pain/no pain) ($P<.05$). ^A^Approaching significance between groups (pain/no pain) ($P<.10$). Abbreviations: CA, contact angle (angle along the arc of the handrim); peakFr, peak resultant force at the handrim; PT, push time (time hand is in contact with handrim).

subjects' average variables changed similarly to previous studies where increased speeds corresponded to higher forces and reduced push time. However, SD and CV also changed significantly with speed. For example, all subjects independent of pain displayed decreased CV with increased speed for temporal-spatial variables. Similar relationships were observed for SD; however, the SD of stroke frequency increased with increasing speed. Although novel to the study of propulsion, these findings are consistent with human space-time accuracy principles where spatial error has been shown to increase as a function of movement time, and temporal error is reduced through reductions of movement speed.[33]

While the CV and SD of timing variables tended to decrease with speed, participants reported extremely low RPE values throughout, suggesting that propulsion conditions such as speed and rolling resistance were not overly challenging. In addition, this study examined these measures in long-term wheelchair users using their own personal wheelchairs. Additionally, all mean propulsion values were recorded based on 3 minutes of steady-state propulsion or up to 190 strokes, which is a considerably longer recording period than in most studies,[2,5,6] where researchers typically record the mean of 5 to 10 strokes.

Selection bias is an inherent challenge to researchers studying wheelchair users experiencing pain.[7] Although participants report pain, the experience of pain is subjective and affects individuals differently. Historically, if pain is severe enough, individuals are typically excluded from participation, do not volunteer, have already switched to power mobility, or may have permanently modified their technique to avoid pain. The individuals with pain in this study overall reported relatively low WUSPI scores that some might consider negligible. However, this could be viewed as a study strength. Despite low pain levels, kinetic and temporal-spatial stroke differences were still detectable, which lends support to variability providing a means for earlier identification of individuals at risk for developing shoulder pain and associated adverse outcomes.

When viewed in combination with previous research, our results suggest that the study of variability has great potential and should be applied to wheelchair user propulsions. Although this pilot study was a first step, it suggests that kinetic and temporal-spatial measures of intra-individual stroke variability at the handrim may be more sensitive to stroke differences caused by pain than traditional biomechanical measures where group differences are not detectable.

Study limitations

A major limitation of the current study was the lack of measures used to assess propulsion technique. Only kinetic and temporal-spatial measures at the handrim were quantified, which do not fully constitute an individual's propulsion biomechanics. Future work should incorporate measures of motion analysis and muscle activity to further characterize propulsion biomechanics. Another limitation of this study was that propulsion occurred on a dynamometer at submaximal levels. Because the study was designed to capture naturally occurring variability caused by pain, it was critical to minimize the occurrence of fatigue because it has been shown to cause distinct variability patterns.[34,35] While it is possible some subjects were more challenged than others, the dynamometer and visual speed feedback system allowed researchers to control subjects' exertion levels. The extent to which the same differences in CV caused by pain or changes in speed translate to more challenging propulsion scenarios is unknown and warrants further investigation. This study also had a relatively small sample size; however, we were still able to find differences caused by pain. In addition, although our subjects had a diverse range of disabilities, these results may not be generalizable to all MWUs. Future work performed on a larger, more diverse group of MWUs is needed to fully characterize the range of variability that constitutes healthy motor adaptation in MWUs.

Conclusions

The mean wheelchair propulsion values of peak force and push time were not different between pain groups. However, the variability of these biomechanical measures of wheelchair propulsion was lower in wheelchair users with shoulder pain. Future work is needed to determine whether relative variability analysis will offer an approach of earlier identification of MWUs at risk for developing shoulder pain and upper limb musculoskeletal disorders.

Suppliers

a. Three Rivers Holdings, LLC, 1826 W Broadway Rd, Ste 43, Mesa, AZ 85202.
b. The MathWorks, Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.
c. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.

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