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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 (MWU).

Design—Cohort

Setting—University Research Laboratory

Participants—26 adults with physical disabilities 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 (WUSPI). Intra-individual mean, standard deviation (SD), and coefficient of variation of (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 ($p > 0.016$). However, individuals with pain displayed less relative variability (CV) in peak resultant force and push time than pain free individuals ($p < 0.016$).

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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. It is proposed that variability analysis may offer an approach of earlier identification of manual wheelchair users at risk for developing shoulder pain.

Keywords

Wheelchair; Biomechanics; Shoulder

There are an estimated 2 million manual wheelchair users (MWU) 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 Due to the adverse consequences of upper extremity pain in manual wheelchair users, 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 moments²⁻⁸ as well as demographic features like years of wheelchair use, gender, 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 MWU 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 of the normal range is indicative of 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 knee¹⁷, shoulder¹⁸, 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 (MSD) 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 if there are differences in intra-individual (e.g. within individual) variability in kinetic and timing propulsion parameters as a function of shoulder pain in full time manual wheelchair users. Based on the extant literature, it was predicted that manual wheelchair users with shoulder pain would demonstrate less kinetic and temporal-spatial variability at the handrim during propulsion compared to those without pain.

Methods

Participants

Twenty-six individuals (10 female, 16 male) from the Urbana-Champaign community volunteered and provided informed consent before participation in this study. All of the participants were manual wheelchair users who used a wheelchair as their primary means of ambulation for more than one year and were between 18-64 years of age. People were excluded from participation if they had upper limb pain that prohibited them from propelling a manual wheelchair. The wheelchair user's diagnosis includes spinal cord injury (thoracic 8 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 pain or no pain group based on self-report of shoulder pain. They were asked if they are currently experiencing shoulder pain and rated their current level of shoulder pain with a 10 cm visual analog scale (VAS)²¹ of 0 (no pain) to 10 (high pain).

Protocol

All experimentation was approved by the local institutional review board. Upon arrival to the laboratory, participants were explained the experimental procedures and 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 (Table 1).

Data Collection

Participants' own wheelchairs were fitted bilaterally with 25 inch diameter SmartWheels^a (Three Rivers Holdings LLC; AZ, USA)^{22,23} 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), 0.7m/s, (slow) and self-select for three minutes. Perceived exertion was quantified after each trial with the BORG perceived exertion scale. Full rest and recovery was provided between trials. The sequence of speeds was randomized 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 Smart Wheel 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 ms.

The Wheelchair Users Shoulder Pain Index (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)-150 (maximum limitations due to pain).

Ratings of perceived exertion (RPE) values were recorded immediately following each propulsion trial using the Borg scale as an index of perceived physiological stress.²⁶ Each participant received detailed instructions about the use of the scale and was given examples of how they might rate differentiated RPE.

Data Reduction

Peak resultant force [peak Fr(N)], peak rate of rise of resultant force [peak ror Fr(N/s)], contact angle [CA(degrees)], stroke frequency [SF(strokes/s)], and push time [PT(s)] were calculated with a custom MATLAB^b program for each trial. Peak Fr is the maximum total force applied to the handrim per stroke cycle, while peak ror Fr 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 average ($\bar{X}$) standard deviation (sd), and Coefficient of Variation (CV). Figure 1 illustrates the peak resultant force at the handrim over three 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 standard deviation (absolute amount of variation) and coefficient of variation (relative variation) (Figure 1).

Statistical analysis

Statistical analyses were conducted using SPSS^c version 21 for Windows. 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, and WUSPI score) were compared using T-test with a Bonferroni correction ($p=0.0125$). The mean, SD, & CV of the dependent variables (peak Fr, peak ror Fr, CA, SF and PT) were compared using a 2 by 3 mixed model MANOVA 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 $0.05/3=0.016$ based on the inclusion of mean, SD, & CV into the MANOVA. 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 $p=0.006$ (Table 1).

Velocity & 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 ($p>0.05$). Perceived exertion scores were low (20-30% effort) for all speed conditions and not significantly different between groups ($p>0.05$). On average, the magnitude of self-selected speeds fell in between the slow and fast conditions for both groups (Table2).

Kinetic and temporal spatial propulsion outcomes

Multivariate Report—The mixed-design MANOVA showed a main effect for pain (Pillai-Bartlett trace=.376, $F(15,61)=2.15$, $P=.01$, $\eta^2=0.34$) and Speed (Pillai-Bartlett trace=.828, $F(30,124)=2.91$, $P<.001$, $\eta^2=0.41$).

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 ($p>0.016$) (Table 3). As expected, stroke frequency increased with faster propulsion speeds, while push time decreased [$F(2,75)=9.8$, $p=.0001$, $\eta^2=.29$], [$F(2,75)=23.2$, $p=.0001$, $\eta^2=.383$](Tables 4).

Absolute Intra-Variation [Standard Deviation (SD)] Propulsion Variables—

Absolute intra-SD in peak Fr was significantly different between pain groups with those with pain being less variable [$F(1,75)=7.5, p=.007, \eta^2=.092$](Table 3). Statistically significant differences in absolute SD were also found based on speed condition ($p < 0.016$). Push time became less variable with speed while stroke frequency became more variable [$F(2,75)=22.8, p=.0001, \eta^2=.379$], [$F(2,75)=4.7, p=.01, \eta^2=.11$], (Tables 4).

Relative Intra-Variation [Coefficient of Variation (CV)] Propulsion Variables—

CV (%) was statistically significant as a function of pain group and speed condition (Figure 2, Tables 3 & 4). For example, individuals who reported pain displayed a reduced CV compared to those without pain in overall push time, peak Fr, and contact angle (approaching significance) [$F(1,75)=7.4, p=.008, \eta^2=.09$]; [$F(1,75)=18.0, p=.0001, \eta^2=.19$]; [$F(1,75)=5.6, p=.02, \eta^2=.06$] (Figure 2, Table 3). All participants, regardless of pain status displayed decreased CV with increased speed for stroke frequency, push time (approaching significance), and Peak for Fr (approaching significance) [$F(2,75)=12.8, p=.0001, \eta^2=.25$]; [$F(2,75)=4.1, p=.02, \eta^2=.09$]; [$F(1,75)=4.2, p=.017, \eta^2=.10$] (Table 4).

Discussion

It was hypothesized that MWU experiencing pain would propel with less variable kinetic and temporal spatial propulsion outcome measures than those pain free. Consistent with our hypothesis, MWU with pain displayed decreased CV in kinetic and temporal-spatial variables (Table 3). These results provide preliminary evidence that CV may serve as unique marker of shoulder pain.

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 FR force production and time spent in propulsion. Although novel to wheelchair propulsion research, these observations are consistent with several reports of movement tasks in which a variety of long-term pain conditions have been associated with reduced motor variability.^{14, 20}

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 two 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 hand rim.

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 MSDs.^{18, 28} The most frequently suggested intervention against MSD caused by repetitive work is to decrease its similarity, i.e. create more 'variation' in biomechanical exposure.²⁹ Importantly, wheelchair propulsion, with a stroke occurring approximately once per second³⁰, far exceeds what the majority of studies consider a repetitive task.^{31, 32}

The average kinetic and temporal spatial propulsion outcomes measures obtained in the present study are fully consistent to the extant wheelchair propulsion literature.^{2, 5, 7, 8} Specifically, the average values observed here were comparable not only in magnitude but similar in the sense that there were no observable differences between the average kinetic and temporal spatial values of MWU with and without pain. In fact, previous studies have found that pain did not alter the way a person propels a wheelchair.^{7, 8} 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 measure 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 subjects average variables changed similarly to previous studies where increased speeds corresponded to higher forces and reduced push time. However, SD and CV also change 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, it is important to note that participants reported extremely low RPE values throughout, suggesting propulsion conditions like 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 considerably larger than a majority of studies, where researchers typically record the mean of 5-10 strokes.^{2, 5, 6}

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 influences individuals differently. Historically, if pain is severe enough, individuals are typically excluded from participation, don't 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 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 hand rim may be more sensitive to stroke differences due to 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 due to 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 subject's exertion levels. The extent to which the same differences in CV due to 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 due to pain. In addition, although our subjects had a diverse range of disabilities, these results may not be generalizable to all MWU. Future work performed on larger more diverse group of MWU is needed to fully characterize the range of variability that constitutes healthy motor adaptation in MWU.

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 if relative variability analysis will offer an approach of earlier identification of manual wheelchair users at risk for developing shoulder pain and upper limb MSD.

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List of Abbreviations

MWU	Manual Wheelchair User
WUSPI	Wheelchair Users Shoulder Pain Index
RPE	Rate of Perceived Exertion
CV	Coefficient of Variation

Figure 1. Representative peak force data and derivation of propulsion outcome variables

X = Mean

sd= Standard deviation

CV= Coefficient of variation

Figure 2. Coefficient of Variation (CV) Group Differences

* Significant difference between groups (pain/no pain) ($p < .05$)

^A approaching significance between groups (pain/no pain) ($p < 0.1$)

CA= Contact Angle (angle along the arc of the hand rim)

peakFr= peak resultant force at the hand rim

PT= Push Time (time hand is in contact with hand rim)

Demographic Characteristics**Table 1**

Characteristics	Pain	No Pain
Subjects (N)	13	13
Mean age (years)	28.5(12.3)	20.9 (4.9)
Sex (M/F)	8/5	8/5
Mean weight (kg)	73.8(25.2)	62.8(14.3)
Mean wheelchair use (years)	15.3(11.4)	12.9(5.3)
WUSPI score	22.3(21.4) *	3.9(5.0)

Notes:

* significant difference, between groups (pain/no pain) ($p < .0125$)

Table 2
Actual speeds with corresponding perceived exertion scores (BORG)

Speed Condition	Group			
	Pain		No Pain	
	Actual Speed	BORG	Actual Speed	Borg
Slow(0.7mps)	0.72(.03)	7.8(2.5)	0.72(.03)	7.6(2.0)
Self	0.92(0.14)	7.9(2.3)	0.93(0.23)	8.1(1.8)
Fast(1.1 mps)	1.12(0.04)	8.0(1.9)	1.14(0.05)	8.6(2.4)

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 rorFr(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(°)	103.1(3.1)	97.3(3.0)	5.3(0.2)	5.9(0.2)	5.2(0.3) ^A	6.5(0.3) ^A
Freq (St/sec)	0.7(0.02)	0.7(0.02)	0.1(0.003)	0.1(0.003)	17.2(0.3)	17.0(0.3)
Push Time (sec)	0.6(0.02)	0.5(0.02)	0.04(0.002)	0.04(0.002)	6.3(0.3)*	7.5(0.3)*

Notes:

All values represented as mean(SE) collapsed for speed (slow, SS, fast)

* significant difference, between groups (pain/no pain) ($p < .016$)

^A approaching significance between groups (pain/no pain) ($p < 0.05$)

Mean= traditional "mean" performance variable

SD= within subject standard deviation (σ)

CV= Coefficient of Variation expressed as % ($\sigma/\mu * 100$)

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

	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 rorFr(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) ^A	22.6 (1.6) ^A	21.0 (1.6) ^A
CA(°)	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)
Frequency (St/sec)	0.6 (0.03) [*]	0.7 (0.03) [*]	0.8 (0.03) [*]	0.11 (0.004) [*]	0.12 (0.004) [*]	0.13 (0.004) [*]	18.4 (0.3) [*]	17.2 (0.3) [*]	15.7 (0.3) [*]
Push Time (sec)	0.7 (0.02) [*]	0.5 (0.02) [*]	0.4 (0.02) [*]	0.05 (0.003) [*]	0.04 (0.003) [*]	0.03 (0.003) [*]	7.7 (0.3) ^A	6.7 (0.3) ^A	6.2 (0.3) ^A

Notes:

All values represented as mean (SE) collapsed for pain

* significant difference based on the main effect of speed ($p < 0.016$)

^A approaching significance based on the main effect of speed ($p < 0.05$)

Mean= traditional "mean" performance variable

SD= within subject standard deviation (σ)

CV= Coefficient of Variation expressed as % ($\sigma/\mu * 100$)