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Scapular kinematic variability during wheelchair propulsion is associated with shoulder pain in wheelchair users

Simon J. Briley [a], Riemer J.K. Vegter [a,b], Vicky L. Goosey-Tolfrey [a], Barry S. Mason [a,*]

[a] Peter Harrison Centre for Disability Sport, School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom
[b] University of Groningen, University Medical Center Groningen, Department of Human Movement Sciences, Groningen, the Netherlands

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ABSTRACT

The purpose of this study was to investigate whether wheelchair propulsion biomechanics differ between individuals with different magnitudes of shoulder pain. Forty (age 36 ± 11 years) manual wheelchair users propelled their own daily living wheelchair at 1.11 $m \cdot s^{-1}$ for three minutes on a dual-roller ergometer. Shoulder pain was evaluated using the Performance Corrected Wheelchair User's Shoulder Pain Index (PC-WUSPI). Correlation analyses between spatio-temporal, kinetic and upper limb kinematic variables during wheelchair propulsion and PC-WUSPI scores were assessed. Furthermore, kinematic differences between wheelchair users with no or mild shoulder pain (n = 33) and moderate pain (n = 7) were investigated using statistical parametric mapping. Participant mean PC-WUSPI scores were 20.3 ± 26.3 points and varied from zero up to 104 points. No significant correlations were observed between kinetic or spatio-temporal parameters of wheelchair propulsion and shoulder pain. However, lower inter-cycle variability of scapular internal/external rotation was associated with greater levels of shoulder pain ($r = 0.35$, $P = 0.03$). Wheelchair users with moderate pain displayed significantly lower scapular kinematic variability compared to those with mild or no pain between 17 and 51% of the push phase for internal rotation, between 31–42% and 77–100% of the push phase for downward rotation and between 28–36% and 53–65% of the push phase for posterior tilt. Lower scapular variability displayed by wheelchair users with moderate shoulder pain may reflect a more uniform distribution of repeated subacromial tissue stress imposed by propulsion. This suggests that lower scapular kinematic variability during propulsion may contribute towards the development of chronic shoulder pain.

1. Introduction

During activities of daily living, such as transferring, weight relief and wheelchair propulsion the shoulder girdle is exposed to highly repetitive forces that may contribute to the development of chronic shoulder pain in manual wheelchair users (van Drongelen et al., 2005). It is easy to recognise that independence and quality of life is diminished as a consequence of the high prevalence of shoulder pain among wheelchair users, making this a topic of great concern (Finley et al., 2004; Gutierrez et al., 2007). That said, the causes of shoulder pain are multifactorial and currently not well known. The biomechanical characteristics of daily propulsion are thought to contribute to the development of chronic shoulder pain in manual wheelchair users and warrant investigation (Dyson-Hudson & Kirshblum, 2004).

Current evidence for an association between shoulder pain and wheelchair propulsion biomechanics is unclear (Collinger et al., 2008; Moon et al., 2013). Biomechanical studies of wheelchair propulsion primarily employ mean spatio-temporal and kinetic measures; however, evidence suggests that these variables are comparable in manual wheelchair users with and without shoulder pain (Moon et al., 2013; Rice et al., 2014). Previous findings are currently limited by the reliance on small study sample sizes and categorising individuals into those with and those without shoulder pain. As a result, examining the association between wheelchair propulsion biomechanics and an individual's level of shoulder pain in a large and diverse sample of manual wheelchair users is required.

Recent evidence suggests that chronic shoulder pain may be better understood by investigating movement variability during wheelchair propulsion (Jayaraman et al., 2014; Moon et al., 2013; Rice et al., 2014). Studies have shown that the inter-cycle variability of spatio-temporal and kinetic parameters of wheelchair propulsion differ between manual wheelchair users with and

* Corresponding author.
E-mail address: b.mason@lboro.ac.uk (B.S. Mason).

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without shoulder pain (Jayaraman et al., 2014; Moon et al., 2013; Rice et al., 2014). However, kinematic variability of upper limb motion has only been evaluated in terms of the spatial variability of distally located joint structures, i.e. the wrist, during the recovery phase of wheelchair propulsion (Jayaraman et al., 2014). The spatial motion and variability of more proximally located joints, namely the shoulder and elbow, may provide more specific information about how the segments of the shoulder and upper arm move. In addition, since the elbow and shoulder joints are less constrained during the push phase it is worth evaluating these joints during both the push and recovery phases of the propulsion cycle. During wheelchair propulsion, wheelchair users exhibit scapular and humeral kinematics that impose mechanical stress on tissues within the shoulder (Morrow et al., 2011; Mozingo et al., 2020). However, it is currently unclear whether these orientations would be more common in wheelchair users with greater levels of shoulder pain. Furthermore, drawing from other research areas it may be expected that reduced inter-cycle variability of scapular or humeral kinematics (joint kinematic variability) may modify the risk of developing chronic shoulder pain (Hamill et al., 2012). Subsequently, the purpose of this study was to investigate the association between wheelchair propulsion biomechanics and the magnitude of shoulder pain in a large and diverse sample of manual wheelchair users. It was hypothesised that greater magnitudes of shoulder pain would be associated with lower scapular and humeral kinematic variability.

2. Methods

2.1. Participants

A convenience sampling strategy was used to enable the recruitment of a large and diverse sample of full-time manual wheelchair users. Participants primarily resided in the local community and were recruited through advertisements, direct contacts and previous study participation. Forty participants (29 men, 11 women; age = 36 ± 11 years; body mass = 75.2 ± 19.4 kg; duration of wheelchair use = 17 ± 12 years) provided written informed consent and completed this study. All participants met the following inclusion criteria: full-time manual wheelchair user, aged 18–55 years. Manual wheelchair users over the age of 55 years old were not included in the study to minimise the influence of older age on both shoulder pain and wheelchair propulsion biomechanics. Primary impairments were inclusive of spinal cord injury (SCI) C6 or below, spina bifida and cerebral palsy. Participants were comprised of both athletic and nonathletic wheelchair users based on our previous work that found no biomechanical differences in daily wheelchair propulsion between these populations (Briley et al., 2020). Ethical approval was obtained through the University's local ethics committee.

2.2. Shoulder pain

Shoulder pain severity experienced during 15 daily life activities was evaluated using the Performance Corrected Wheelchair User Shoulder Pain Index (PC-WUSPI) (Curtis et al., 1995, 1999). The PC-WUSPI uses a 10 cm visual analogue scale (VAS) for each activity. The total score was reported as the sum of the activities scores divided by the number of activities the participant performed multiplied by 15 to provide a total score between 0 (no pain) and 150 (highest degree of pain).

2.3. Experimental protocol

Participants physical characteristics (age, body mass, sex, primary impairment, years of wheelchair use and physical activity) and wheelchair configuration of their own daily living wheelchair (chair mass, wheel diameter, rim diameter and wheelbase) were measured upon arrival at the laboratory. Participant's wheelchair characteristics were chair mass 12.6 ± 1.7 kg; wheel diameter 0.61 ± 0.01 m; rim diameter 0.55 ± 0.01 m and wheelbase 0.54 ± 0.05 m. Participants wheelchairs were then attached to a dual roller wheelchair ergometer (Lode Esseda, m988900, Groningen, Netherlands). Participants completed a five-minute warm up involving wheelchair propulsion at a self-selected speed and dynamic stretching. The propulsion trial involved participants performing three-minutes of submaximal propulsion at a speed, of 1.11 $m{\cdot}s^{-1}$, that is reflective of everyday propulsion (Mason et al., 2014). Participants maintained the prescribed speed by following a visual real-time display of the combined speed of the left and right rollers.

2.4. Kinematics

Upper limb kinematics during wheelchair propulsion were captured using a 10 camera (MX T40-S) Vicon motion analysis system (Vicon, Motion Systems Ltd. Oxford, UK) with a frame rate of 200 Hz. Eighteen 14 mm retroreflective markers (B&L Engineering, California, USA) were attached to anatomical landmarks of both upper limbs and the torso following International Society of Biomechanics (ISB) recommendations (Wu et al., 2005). Acromion marker clusters (AMC) were used to track scapular orientation during wheelchair propulsion (Warner et al., 2015). The AMC method establishes the relative position of the acromial angle (AA), trigonum scapulae (TS) and inferior angle (AI) of both scapula to the AMC using a calibration wand during a static trial (Karduna et al., 2001) This known relationship was used to reconstruct scapular landmarks for the propulsion trial. The validity and reliability of the AMC technique has previously been established for humeral elevation up to 90° (Karduna et al., 2001, Warner et al., 2015) and as a reliable method (typical error <3.2°) during wheelchair propulsion (Mason et al., 2018). Glenohumeral joint centre (GHJC) positions were determined using the Symmetrical Centre of Rotation Estimation (SCoRE) method from a bilateral circumduction trial (Ehrig et al., 2006).

2.5. Data analysis

The following kinetic and spatio-temporal variables were calculated from the wheelchair ergometer according to previous studies: stroke frequency, push time, recovery time, contact angle, contact angle coefficient of variation (CV), peak torque and work done per push (Goosey-Tolfrey et al., 2018, Mason et al., 2014, Vegter et al., 2013). Initial push rim contact and release were identified by a threshold of 1 Nm from the ergometer data (Vegter et al., 2013). Marker trajectories collected from the motion capture system were filtered using a fourth-order, low-pass Butterworth filter with a cut off frequency of 6-Hz (Morrow et al., 2011). Euler angles were calculated for scapulothoracic (scapula to thorax) and humerothoracic (humerus to thorax) motion (Kontaxis et al., 2009, Wu et al., 2005). For individuals with unilateral shoulder pain the painful side was analysed, for those with bilateral pain the most painful side was analysed. Joint centre displacements of the glenohumeral, elbow and wrist joints relative to the wheel axel and scapulothoracic and humerothoracic joint angles were time-normalised for the push phase and recovery phase separately. The mean and standard deviation of joint displacements and joint angles at each time normalised point were extracted from 20 consecutive propulsion cycles of each participant during the final 60 s of the propulsion trial.

2.6. Statistical analysis

All statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS Version 23, IBM, New York, USA). Data was assessed for normality using Shapiro-Wilk tests. A one-way independent analysis of variance (ANOVA) was used to assess the effect of impairment type on PC-WUSPI scores. Spearman's rank order correlation analyses were used to evaluate the relationship between participants PC-WUSPI scores and discrete spatio-temporal, kinetic and joint kinematic parameters of wheelchair propulsion. Mean, minimum, maximum and range of motions (ROM) were calculated for scapulothoracic and humerothoracic angles. In addition, the mean, minimum and maximum inter-cycle variability of the joint angles were calculated using the standard deviation of 20 consecutive propulsion cycles.

Statistical Parametric Mapping (SPM) independent t-tests were used to further investigate the association between upper limb kinematics and shoulder pain magnitude (Pataky et al., 2013). Participants were retrospectively categorised as having no/mild, moderate or severe shoulder pain according to PC-WUSPI scores. Previous work by Boonstra et al. (2014) reported that the most appropriate thresholds for describing chronic musculoskeletal pain were VAS scores of $\leq$3.4 for mild pain, between 3.5 and 7.4 for moderate pain and $\geq$7.5 for severe pain. These thresholds were matched to the PC-WUSPI scale of 0–150 by multiplying each value by 15. The thresholds were applied to PC-WUSPI scores because this outcome measure has been shown to be valid and reliable for wheelchair users and is commonly utilised for research into wheelchair user's shoulder pain (Curtis et al., 1995, 1999). Therefore, participants that reported a PC-WUSPI score of $\leq$51 were classified as no or mild pain, between 52.5 and 111 moderate pain and >112.5 severe pain. For grouped kinematic comparisons to achieve a statistical power of 80% (P = 0.05) based on the data of Mason et al. (2018) a minimum of seven participants were required per pain group (G*Power, 3.1.9.2). SPM independent t-tests (α = 0.05) were used to identify regions of the push phase and recovery phase of the propulsion cycle where significant differences in the kinematic trajectories occurred. Normality of the kinematic waveforms were assessed prior to the analysis. All SPM analyses were performed using open-source MATLAB code (SPM1d, v.M0.4.5, www.spm1d.org), with detailed descriptions of SPM theory and methods provided elsewhere (Pataky et al., 2013).

3. Results

Mean PC-WUSPI scores were 20.3 ± 26.3 points (Fig. 1). Of the 40 participants, 33 (82.5%) were categorised as having no/mild shoulder pain and seven (17.5%) moderate shoulder pain (Fig. 1). No significant main effect for impairment type on shoulder pain ($F_{(1,3)}$ = 0.65, P = 0.59) was observed. In addition, both pain groups (mild and moderate pain) were composed of a mixture of impairment types.

No significant correlations between any kinetic or spatio-temporal parameters of wheelchair propulsion and shoulder pain were observed (Table 1). Lower scapular internal/external rotation variability was significantly correlated with higher shoulder pain (Table 2).

Mean joint displacements and joint displacement inter-cycle variability of the glenohumeral, elbow and wrist joint centres were not significantly different between wheelchair users with moderate pain and those with mild pain during either the push or recovery phases (Fig. 2).

SPM t-tests reported no significant differences for mean scapular or humeral kinematics (Fig. 3 and Fig. 4). During the push phase wheelchair users with moderate pain displayed significantly lower scapular kinematic variability compared to those with mild pain (Fig. 3). Specific differences in scapular kinematic variability occurred between 17 and 51% of the push phase for internal rotation, between 31–42% and 77–100% of the push phase for downward rotation and between 28–36% and 53–65% of the push phase for posterior tilt (Fig. 3). Humeral kinematic variability was not significantly different across either the push or recovery phases of wheelchair propulsion (Fig. 4).

4. Discussion

The current study compared wheelchair propulsion biomechanics in wheelchair users according to shoulder pain severity. Importantly, this study enabled an examination of the distribution of shoulder pain severity within a typical cohort of young manual wheelchair users, so far lacking in the scientific literature. In support of the study hypothesis lower scapular internal/external rotation kinematic variability correlated with greater shoulder pain. In addition, the grouped kinematic analysis observed that wheelchair users with moderate shoulder pain exhibited lower kinematic variability across all scapular angles during the push phase compared to those with mild pain.

No association between spatio-temporal and kinetic parameters of propulsion and shoulder pain was observed. These findings support previous studies that report no differences in mean spatio-temporal or kinetic parameters of propulsion between those with and without shoulder pain (Collinger et al., 2008; Rice et al., 2014). In addition, the correlation between scapular variability and shoulder pain indicates that other biomechanical parameters such as movement variability may help better understand shoulder pain amongst wheelchair users. However, to qualify this statement it should be noted that this correlation was reported for scapular internal rotation only.

Due to the large and diverse sample of manual wheelchair users recruited in this study an examination of shoulder pain is possible. Of the forty participants, twenty-eight (70%) reported some form of shoulder pain (PC-WUSPI > 0) which is similar to that reported in other studies (Finley et al., 2004). A detailed examination of the distribution of shoulder pain revealed that within this sample PC-WUSPI scores varied widely with maximum score of 104 points. It was observed that seven (17.5%) participants were classified with moderate pain. The marked difference in PC-WUSPI scores reported by those with moderate pain suggest that the threshold utilised in this study to distinguish between wheelchair users with mild and moderate shoulder pain is suitable for this cohort of wheelchair users. Previous studies have predominantly investigated wheelchair propulsion between wheelchair users with and without pain irrespective of the magnitude of individuals shoulder pain symptoms. This study presents an important first step in establishing PC-WUSPI thresholds that can be applied to other investigations of wheelchair propulsion biomechanics to enable a more thorough understanding and new perspectives of chronic shoulder pain development in wheelchair users.

In contrast to a previous study no differences in wrist spatial variability were observed between pain groups (Jayaraman et al., 2014). Furthermore, no differences were found in joint displacement or spatial variability in more proximally located joints (glenohumeral and elbow). Therefore, the current study cannot support previous work that indicated wheelchair users with shoulder pain display significantly greater wrist spatial variability during recovery phase compared to no pain.

A notable finding of the current study was that wheelchair users with moderate shoulder pain exhibited significantly lower scapular kinematic variability during the push phase of wheelchair propul-

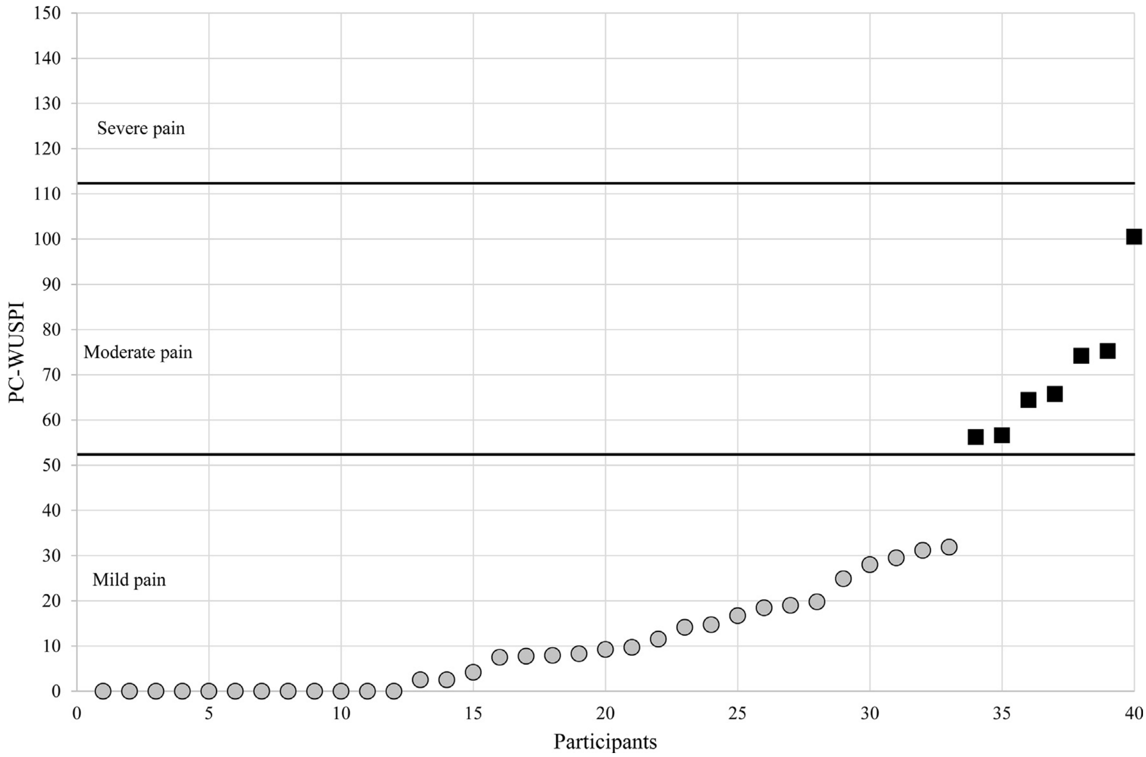

Fig. 1. Individual PC-WUSPI scores and divisions of pain groupings. Wheelchair users with no or mild pain (PC-WUSPI ≤ 51) n = 33 and moderate pain (52.5 ≤ 111) n = 7.

Table 1
Relationships between spatio-temporal and kinetic characteristics during wheelchair propulsion at 1.11 m.s^{-1} and shoulder pain according to PC-WUSPI.

Variable	Mean(SD)	r	P
SF (push/min)	52(13)	−0.12	0.46
Push time (sec)	0.37(0.07)	0.13	0.41
Rec time (sec)	0.76(0.15)	−0.09	0.56
Initial contact ang (°)	−23.9(12.0)	−0.01	0.95
Release angle (°)	51.6(11.9)	0.24	0.13
Contact angle (°)	79.2(16.5)	0.15	0.35
Contact angle CV (%)	6.01(2.97)	0.004	0.98
Peak Torque (N.m)	14.5(5.01)	0.04	0.80
Work done per push (J)	13(5)	0.15	0.36

n.b. SF = Stroke frequency.

sion compared to those with no/mild shoulder pain. Previous work has only evaluated kinematic variability of distally located joints during the recovery phase of wheelchair propulsion (Jayaraman et al., 2014). However, this study suggests important kinematic information related to shoulder pain may be occurring in the orientation of proximal joints during the push phase. Specifically, all wheelchair users exhibited mean scapular and humeral kinematics (an internally rotated, downwardly rotated scapula and abducted humerus) that may impose stress on the subacromial tissue within the shoulder complex (Morrow et al., 2011, Mozingo et al., 2020). Therefore, it is postulated that more uniform (less variable) scapular kinematics displayed by wheelchair users with moderate shoulder pain may impose this repeated stress on a small tissue area (Hamill et al., 2012). In contrast, the greater variety of scapular orientations displayed by those without pain allows the tissue stress to be distributed over a larger area. As the upper limbs experience highly repetitive forces during daily wheelchair propulsion, low scapular variability may result in greater cumulative tissue fatigue, contributing to the development of chronic shoulder pain in wheelchair users (van Drongelen et al., 2005; Hamill et al., 2012). This proposed mechanism could be extrapolated to those with severe shoulder pain; although, this would require further study. If this explanation is true, then focused interventions or monitoring techniques could be developed to assist manual wheelchair users in creating more varied scapular kinematics during wheelchair propulsion. Alternatively, reduced scapular variability may reflect an adaptive strategy to minimise shoulder pain.

4.1. Study limitations

The inclusion of manual wheelchair users irrespective of disability may be a limitation of this study. However, it should also be reiterated that the purpose of this research was to investigate wheelchair propulsion biomechanics in relation to shoulder pain magnitude in a diverse sample of wheelchair users. As such, this varied sample of wheelchair users has allowed a detailed kinematic analysis of wheelchair propulsion in relation to shoulder pain that may be transferable to the wider wheelchair user population. It is important to note that the moderate pain group composed of both athletic and nonathletic manual wheelchair users which reinforces the generalisability of these results. Importantly, there was no main effect of impairment type on shoulder pain and participant disabilities were equally distributed in both pain groups. It may also be a strength of this study that kinematic differences were observed despite the variety of disabilities within this sample.

It is important to note that the mild pain group used in the current study consisted of twelve participants with PC-WUSPI scores of zero. This was decided because PC-WUSPI scores reported by many individuals with mild pain were very low and resulted in no clear cut off between participants with no or mild pain. This highlights the problem in attempting to transform a continuous variable (PC-WUSPI score) to categorical pain groupings for wheelchair users with mild pain (Boonstra et al., 2014). Furthermore, as large inter-individual differences in kinematic variability were present in the mild pain group alternative approaches may be neces-

Table 2
Relationships between scapulothoracic, humerothoracic kinematics during wheelchair propulsion at 1.11 m·s^{-1} and shoulder pain according to PC-WUSPI. Significant correlations are indicated by bold text.

	Scapulothoracic angles								
Variable	Int(+)/external(−) rotation (°)			Down(+)/up(−) rotation (°)			Posterior(+)/anterior(−) tilt (°)		
	Mean(SD)	r	P	Mean(SD)	r	P	Mean(SD)	r	P
Mean (°)	23.5(6.36)	−0.07	0.69	1.01(1.46)	0.10	0.53	−11.1(6.51)	−0.11	0.49
Max (°)	34.3(8.19)	−0.08	0.64	14.3(6.97)	−0.09	0.59	−4.17(6.09)	−0.02	0.90
Min (°)	14.6(6.98)	−0.06	0.73	5.07(6.90)	−0.21	0.20	−18.1(8.65)	−0.13	0.43
ROM (°)	19.6(8.14)	−0.07	0.68	9.26(3.60)	0.16	0.34	13.9(5.09)	0.12	0.45
Intercycle var. (°)	**1.39(0.72)**	**−0.35**	**0.03**	1.16(0.43)	0.00	0.98	1.09(0.44)	−0.02	0.90
Peak intercycle var. (°)	2.17(1.10)	−0.08	0.64	1.81(0.70)	0.22	0.18	1.94(0.97)	0.24	0.14
Min intercycle var. (°)	**0.87(0.45)**	**−0.33**	**0.04**	0.72(0.33)	−0.14	0.40	0.60(0.31)	−0.26	0.11
	Humerothoracic angles								
Variable	Flexion(+)/extension(−)			Add(+)/abduction(−)			Int(+)/external(−) rotation		
	Mean(SD)	r	P	Mean(SD)	r	P	Mean(SD)	r	P
Mean (°)	−15.3(12.1)	−0.14	0.38	−27.4(6.92)	−0.08	0.64	14.7(13.0)	0.08	0.60
Max (°)	23.1(17.9)	−0.03	0.85	−18.6(6.23)	−0.11	0.48	39.5(16.7)	0.22	0.16
Min (°)	−45.0(9.52)	−0.08	0.63	−34.7(7.93)	−0.04	0.82	−4.67(14.5)	0.13	0.44
ROM (°)	68.2(13.1)	0.08	0.62	16.0(5.38)	−0.08	0.64	44.2(15.2)	0.10	0.53
Intercycle var. (°)	2.94(1.45)	0.00	0.99	1.56(0.58)	−0.06	0.72	3.00(1.33)	−0.06	0.70
Peak intercycle var. (°)	5.56(3.43)	0.04	0.80	2.61(1.45)	−0.03	0.85	5.28(2.49)	0.06	0.72
Min intercycle var. (°)	1.23(0.64)	−0.25	0.12	0.86(0.37)	−0.27	0.09	1.52(0.74)	−0.17	0.30

n.b. ROM = Range of motion.

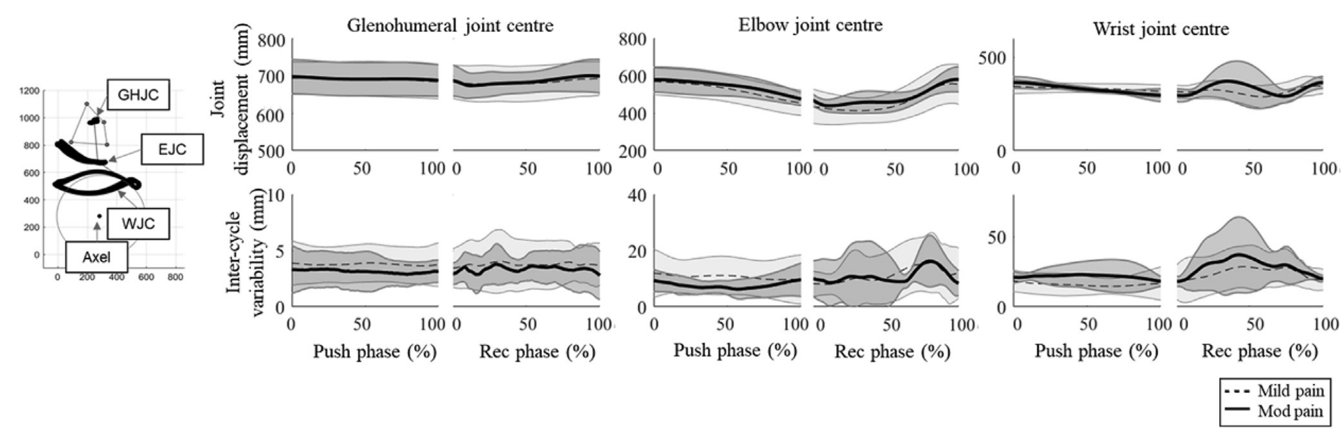

Fig. 2. Comparison of (top) group mean joint displacements relative to the wheel axle (mean kinematic trajectory ± SD cloud) and (bottom) joint spatial variability of the glenohumeral joint centre (GHJC), elbow (EJC) and wrist (WJC) between wheelchair users with moderate pain (solid line) and mild pain (dashed line). Shaded regions indicate significant differences between groups with P values provided for each supra – threshold cluster.

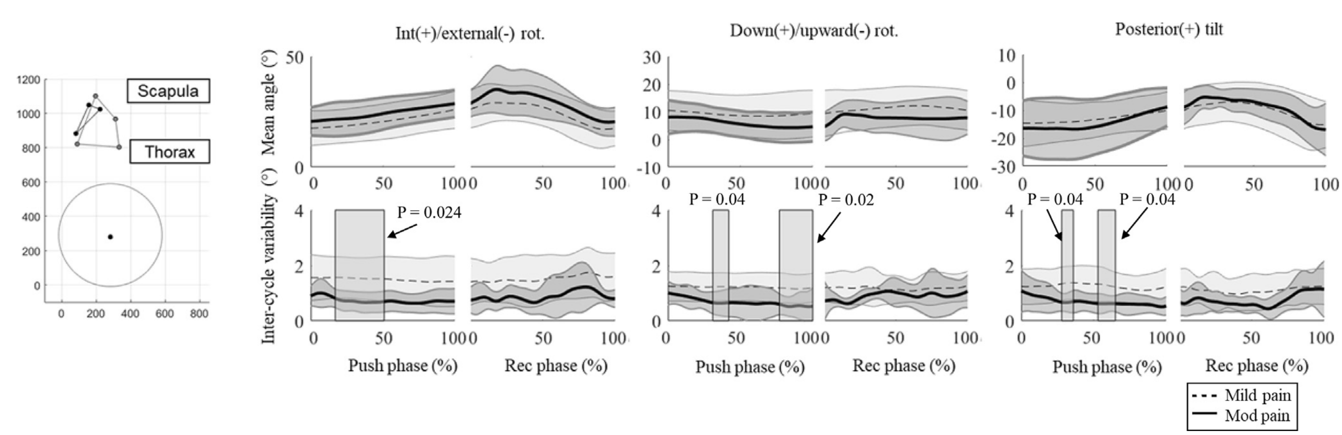

Fig. 3. Comparison of group (top) mean scapulothoracic kinematics (mean kinematic trajectory ± SD cloud) and (bottom) scapulothoracic kinematic variability for wheelchair users with moderate pain (solid line) and mild pain (dashed line). Shaded regions indicate significant differences between groups with P values provided for each supra – threshold cluster.

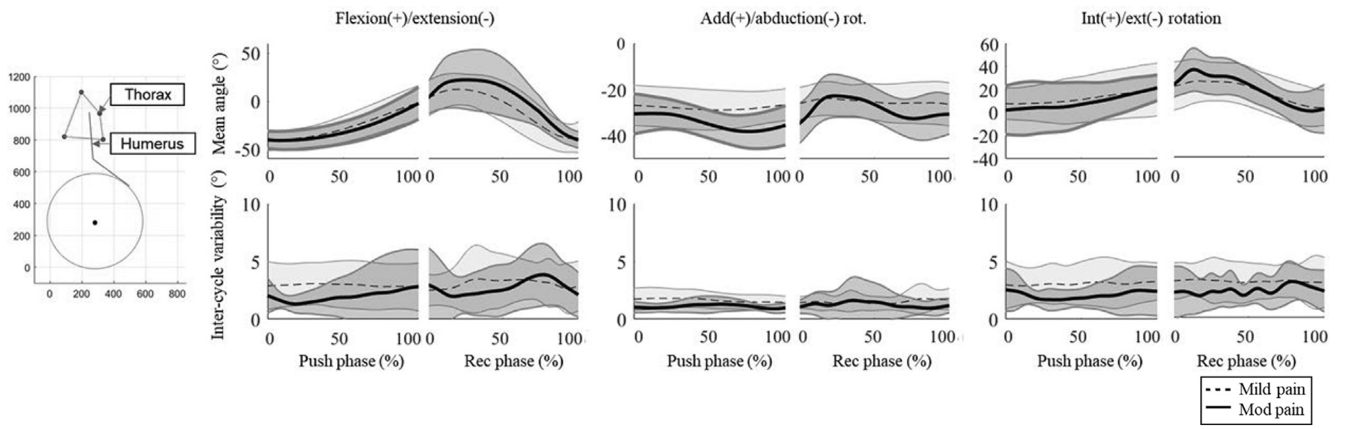

Fig. 4. Comparison of group (top) mean humerothoracic kinematics (mean kinematic trajectory ± SD cloud) and (bottom) humerothoracic kinematic variability for wheelchair users with moderate pain (solid line) and mild pain (dashed line). Shaded regions indicate significant differences between groups with P values provided for each supra – threshold cluster.

sary to address wheelchair users with mild shoulder pain. The authors suggest three research avenues to address those with lower/mild pain symptoms. Firstly, pain thresholds specific to the PC-WUSPI should be developed which may require two subgroups for those with mild pain. Secondly, groups could be classified according to pain symptoms during specific tasks within WUSPI with individuals classified separately according to tasks that require high loading (i.e. transfers), wheelchair propulsion or large ranges of motion. Thirdly, studies could investigate within-subject alterations in wheelchair propulsion biomechanics in relation to changes in pain symptoms over a longitudinal period as pain symptoms may be specific to an individual.

5. Conclusions

The current study revealed that lower scapular kinematic variability during wheelchair propulsion was associated with greater shoulder pain in manual wheelchair users. Lower scapular kinematic variability may cause greater cumulative tissue fatigue and contribute towards shoulder pain development. This information may help direct avenues of future investigations and interventions addressing shoulder pain of wheelchair users.

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