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Predictors of shoulder pain in manual wheelchair users

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ABSTRACT

Background: Manual wheelchair users rely on their upper limbs to provide independent mobility, which leads to high muscular demand on their upper extremities and often results in shoulder pain and injury. However, the specific causes of shoulder pain are unknown. Previous work has shown that decreased shoulder muscle strength is predictive of shoulder pain onset, and others have analyzed joint kinematics and kinetics, propulsion technique and intra-individual variability for their relation to shoulder pathology. The purpose of this study was to determine in a longitudinal setting whether there are specific biomechanical measures that predict shoulder pain development in manual wheelchair users.

Methods: All participants were asymptomatic for shoulder pain and categorized into pain and no pain groups based on assessments at 18 and 36 months later. Shoulder strength, handrim and joint kinetics, kinematics, spatiotemporal measures, intra-individual standard deviations and coefficients of variation were evaluated as predictors of shoulder pain.

Findings: Individuals who developed shoulder pain had weaker shoulder adductor muscles, higher positive shoulder joint work during recovery, and less trunk flexion than those who did not develop pain. In addition, relative intra-individual variability was a better predictor of shoulder pain than absolute variability, however future work is needed to determine when increased versus decreased variability is more favorable for preventing shoulder pain.

Interpretation: These predictors may provide insight into how to improve rehabilitation training and outcomes for manual wheelchair users and ultimately decrease their likelihood of developing shoulder pain and injuries.

1. Introduction

There are currently 3.7 million wheelchair users in the United States (Brault, 2012), with 90% of these using manual wheelchairs (Kaye et al., 2000). Manual wheelchair users (MWCU) rely on their upper limbs to provide independent mobility, which leads to high muscular demand on their upper extremities. This increased demand often results in shoulder pain and injury (Waring and Maynard, 1991) that can lead to decreased quality of life (Gutierrez et al., 2007). However, the specific causes of shoulder pain are unknown. Two studies have analyzed shoulder muscle strength and found that decreased strength was a predictor of shoulder pain onset (Mulroy et al., 2015; van Drongelen et al., 2006). Others have looked at joint kinematics and kinetics and propulsion technique (e.g., contact angle, cadence) and their relation to shoulder pain or injury (Eriks-Hoogland et al., 2014; Mercer et al., 2006; Mulroy et al., 2006, 2015). However, one challenge to such studies is that the demand placed on the upper extremity cannot be measured directly, and therefore causal mechanisms are difficult to identify.

Studies have used joint kinetics as a surrogate measure for muscle demand (Desroches et al., 2010; Kulig et al., 1998, 2001; Price et al., 2007; Sabick et al., 2004) and found that higher shoulder joint forces and moments are associated with upper limb pain (Mulroy et al., 2006) and pathology (Mercer et al., 2006) in MWCU. However, only one of those studies was longitudinal, and therefore able to suggest a link between a higher vertical component of the shoulder joint force and the development of shoulder pain (Mulroy et al., 2006). Joint work is another measure used to quantify muscle demand that is often analyzed in gait to provide insight into mechanical efficiency as well as to identify compensatory mobility strategies in various patient populations (DeVita and Hortobagyi, 2000; Olney et al., 1991; Ventura et al., 2011). To our knowledge, the only study that has analyzed joint work during

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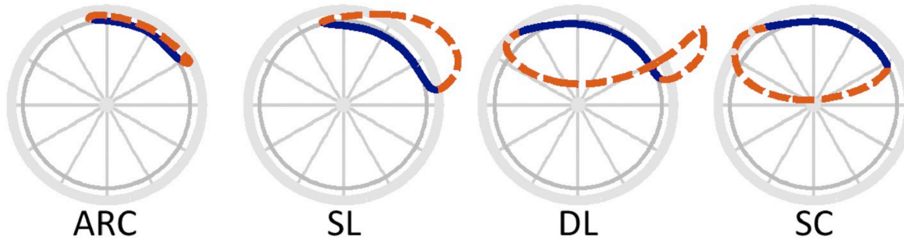

Fig. 1. The four primary hand patterns used during manual wheelchair propulsion: arcing (ARC), single loop (SL), double loop (DL), and semi-circular (SC) (Slowik et al., 2016).

wheelchair propulsion assessed the difference between two methods for calculating upper extremity work and found that the upper extremity supplies more power than is necessary for wheelchair propulsion (Guo et al., 2003). This is similar to the finding that power produced about the shoulder joint is higher than that produced at the elbow and wrist (Price et al., 2007), which may be a contributing factor to the development of shoulder pain. Thus, joint work may be useful in assessing upper extremity effort as it incorporates both shoulder kinetics (joint moment) and kinematics (angular velocity) to determine joint power, which is integrated over time, and thus quantifies sustained upper limb effort.

The recovery hand patterns used by MWCU influences biomechanical variables such as cadence, contact angle and contact percentage, which may be risk factors for developing shoulder pain (Fig. 1). The literature suggests that using lower cadence (Mulroy et al., 2006; Rankin et al., 2012), increased contact angle (Mulroy et al., 2006; Paralyzed Veterans of America Consortium for Spinal Cord Medicine, 2005) and increased contact percentage (Paralyzed Veterans of America Consortium for Spinal Cord Medicine, 2005) can lead to decreased demand on the upper extremity and the likelihood of developing pain and injuries. A number of studies have shown that semi-circular (SC) and double-loop (DL) patterns are associated with decreased cadence and increased contact angle (Boninger et al., 2002; Kwarciak et al., 2012; Qi et al., 2014) and also require less muscle power and stress than arcing (ARC) and single loop (SL) patterns (Slowik et al., 2016). However, the propulsion pattern used has not yet been directly related to the development of shoulder pain and injury.

In highly repetitive tasks such as wheelchair propulsion, analyzing intra-individual variability may be able to distinguish those who are at a higher risk of developing pain or injuries. Recent studies have shown that MWCU with shoulder pain have significantly lower cycle-to-cycle variability in peak total shoulder joint force (Moon et al., 2013), peak total handrim force and push time (Rice et al., 2014). Other work has found that kinematic spatial variability in the wrist motion is higher at the beginning of the recovery phase in those with shoulder pain than those without pain (Jayaraman et al., 2014). Although recent work has shown differences in intra-individual variability between groups of MWCU with and without shoulder pain, it is not yet known if variability is a reaction to the presence of pain or part of the pathomechanics causing shoulder pathology and pain.

The purpose of this study was to determine whether there are specific biomechanical measures that predict whether a manual wheelchair user is likely to develop shoulder pain over time. Specifically, we hypothesized that individuals with higher shoulder joint work, higher shoulder joint moments, higher handrim forces, decreased cycle-to-cycle variability and those using a more over-rim hand pattern will be more likely to develop shoulder pain over time. We also expect that the effect of shoulder strength on the shoulder joint kinetics will better predict shoulder pain development than joint kinetics alone. If these modifiable risk factors can be identified, we can further investigate them as potential targets for interventions to prevent the development of shoulder pain and injury.

2. Methods

2.1. Subjects

Experimental data were collected and analyzed from 102 individuals with paraplegia (93 men, 9 women; age: mean = 36.2 years, SD = 9.6 years; time from injury: mean = 9.5 years, SD = 6.5 years; height: mean = 1.74 m, SD = 0.09 m; mass: mean = 73.9 kg, SD = 15.9 kg). Participants were recruited from outpatient clinics from the Rancho Los Amigos National Rehabilitation Center and gave informed written consent in accordance with the Institutional Review Board. Participants were required to be asymptomatic for shoulder pain at the time of the initial baseline data collection ($<$ 12 points on the Wheelchair User's Shoulder Pain Index, WUSPI) (Curtis et al., 1995), and were excluded from study participation if a history of shoulder injury or surgery was present (Mulroy et al., 2015). Participants were categorized into either the pain (P) or no pain (NP) group based on whether they experienced an increase of $\geq$10 points on the WUSPI from baseline at either the 18-month or 36-month follow-up assessment (Mulroy et al., 2015).

2.2. Data collection

Participants propelled their own wheelchair on a stationary ergometer (Fig. 2) at their comfortable, self-selected speed (mean = 1.00 m/s, SD = 0.26 m/s) for a 40-second trial with data collected during the last 10 s. Three-dimensional kinetic data were measured from the handrim on the right side using an instrumented wheel (SmartWheel; Three Rivers Holdings, Mesa, AZ, USA) at 200 Hz. Kinematic data were collected from the trunk, right-side upper extremity and wheel using a CODA motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK) at 100 Hz with 15 active markers placed on body segment landmarks and right wheel (e.g. Lighthall-Haubert et al., 2009). Shoulder strength was measured as peak maximal isometric torque of the shoulder flexors, extensors, abductors, adductors, internal rotators and external rotators using a Biodex System 3 Pro dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA).

2.3. Data processing

Kinematic and kinetic data were processed using a low-pass, fourth-order, zero-lag Butterworth filter with cutoff frequencies of 6 and 10 Hz, respectively, in Visual 3D (C-Motion, Inc., Germantown, MD, USA). A threshold of 5 N for the resultant handrim force was used to indicate the beginning and end of the contact and recovery phases. Trunk and shoulder angles were calculated in Visual 3D using the International Society of Biomechanics recommendations (Wu et al., 2005). Ranges of motion (RoM), average, maximum and minimum for these angles, peak and average handrim forces, cadence, contact time, contact angle and contact percentage were calculated for each cycle and averaged across cycles for each subject (Table 1). The third metacarpophalangeal joint center (MCP3) was located using a method described previously (Rao et al., 1996), and the path of the MCP3 was

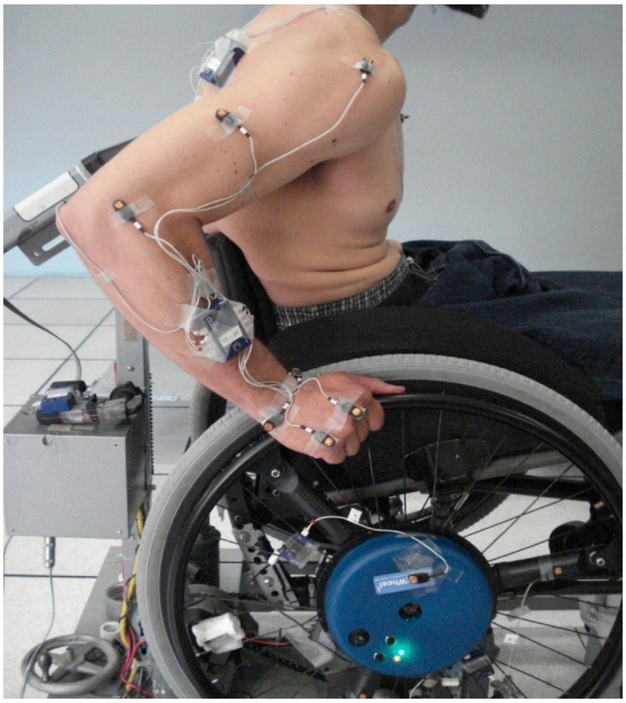

Fig. 2. Experimental setup used to collect kinematics and kinetics on a custom-built wheelchair ergometer.

projected onto the handrim plane and averaged across cycles. This closed-curve hand path was then used to calculate two quantitative parameters to characterize the hand pattern: net radial thickness (NRT) and total radial thickness (TRT), which quantify the hand's displacement above the handrim and the absolute distance between the hand and handrim, respectively, using a previously described method (Slowik et al., 2015). Peak and average shoulder joint moments were calculated for the contact and recovery phases using inverse dynamics in Visual 3D for each cycle, and averaged across cycles for each subject. Shoulder joint power was calculated in Visual 3D and exported to custom code in Matlab (Mathworks Inc., Natick, MA, USA) in order to calculate shoulder joint work. Positive and negative shoulder joint work were calculated for the contact and recovery phases for each cycle and averaged across cycles for each subject. Cycle-to-cycle variability was measured for each subject by calculating the absolute variability as the standard deviation (SD) and calculating the relative variability as the coefficient of variation (CV = SD / |mean|) across all cycles for each parameter (Table 1). All dependent measures were calculated for the right side only because all subjects were asymptomatic for shoulder pain at the time of data collection, and were assumed to have bilateral symmetry (Soltau et al., 2015).

2.4. Statistical analyses

To determine which parameters were predictors of shoulder pain development, variables were organized into nine groups and a stepwise logistic regression procedure was performed in Matlab. Sub-model groups included 1) Strength measures, 2) Handrim kinetics, 3) Joint kinetics, 4) Handrim and joint kinetics, 5) Handrim kinetics, joint kinetics and strength, 6) Kinematics, 7) Spatiotemporal variables, 8) SDs, and 9) CVs as potential predictors. Strength measures included in sub-model 1 included shoulder flexors, adductors and external rotators in order to represent all functional muscle groups without introducing multicollinearity (e.g., Mulroy et al., 2015). In each sub-model, variables that were highly correlated (e.g., variance inflation factor, VIF ≥ 5) to another variable were removed as potential predictors from the model. Forward stepping was conducted with a *P*-value of < 0.1 to enter and ≥0.1 to remove based on the *F*-test of the change in deviance as the criterion for adding or removing a variable. Once all regression models were complete, predictors from all models with a *P*-value < 0.1 were added to a final model. Predictors with VIF ≥ 5 were removed, and then a logistic regression was run on the final predictors using k-fold cross-validation with k = 5 subject groups. The five subject

Table 1
Definition of parameters analyzed.

Variable name	Abbreviation	Definition
Kinematics: RoM, max and min		
Trunk angle [°]		Angle of trunk position relative to the lab vertical axis
Plane-of-elevation [°]		Humerus angle relative to the trunk about the vertical axis
Elevation angle [°]		Humerus angle about its forward axis
Internal/external rotation [°]		Humerus angle about its longitudinal axis
Handrim kinetics: Peak and average		
Tangential force [N]	F_{tan}	Tangential force applied to the handrim
Radial force [N]	F_{rad}	Radial force applied to the handrim
Lateral force [N]	F_{lat}	Lateral force applied to the handrim
Total force [N]	F_{tot}	$F_{tot} = \sqrt{F_{tan}^2 + F_{rad}^2 + F_{lat}^2}$
Spatiotemporal measures		
Contact time [s]		Amount of time spent in the contact phase (based on handrim force threshold of 5 N)
Cycle time [s]		Amount of time spent in the full propulsion cycle
Contact percentage [%]		Percentage of the propulsion cycle spent in the contact phase
Contact angle [°]	θ	Angle between the positions of the hand between the start and end of the contact phase
Net radial thickness [m]	*NRT*	Displacement of the hand above the handrim
Total radial thickness [m]	*TRT*	Distance between the hand and handrim
Joint kinetics: for contact, recovery and full cycle		
Peak and average flexion/extension moment [mm]	M_x	Peak and average reaction moment at the shoulder joint about the mediolateral axis, normalized by body weight
Peak and average ad/abduction moment [mm]	M_y	Peak and average reaction moment at the shoulder joint about the forward axis, normalized by body weight
Peak and average int/external rotation [mm]	M_z	Peak and average reaction moment at the shoulder joint about the humerus longitudinal axis, normalized by body weight
Positive shoulder joint work [mm]	W_{pos}	Integral of the shoulder joint power (dot product of the shoulder joint moment and angular velocity) for Power > 0
Negative shoulder joint work [mm]	W_{neg}	Integral of the shoulder joint power (dot product of the shoulder joint moment and angular velocity) for Power < 0

Table 2
Variables included as predictors in the final model. CV variables are represented as a percentage (SD / |mean| * 100). Shoulder joint work and moments were normalized by body weight (N-mm/N).

Variable name
Strength measures
Adductor torque [N-m]
Handrim kinetics
Average tangential force [N] (+forward at top dead center, TDC/−backward at TDC)
Average radial force [N] (+outward/−inward)
Joint kinetics
Average flexion/extension moment during contact [mm] (+flexion/−extension)
Average adduction/abduction moment during recovery [mm] (+adduction/−abduction)
Negative shoulder joint work during contact [mm]
Positive shoulder joint work during recovery [mm]
Kinematics
Maximum trunk angle [°] (+extension/−flexion)
SDs
Minimum trunk angle SD [°] (+extension/−flexion)
CVs
Average tangential force CV [%]
Average radial force CV [%]
Contact angle CV [%]
Average adduction/abduction moment during contact CV [%]
Interactions
Adduction torque [N-m] * average flexion/extension moment during contact [mm]
Average tangential force [N] * average flexion/extension moment during contact [mm]
Average flexion/extension moment during contact [mm] * negative shoulder joint work during contact [mm]

groups were chosen using a random number generator, and for each of the five iterations of the cross-validation procedure, the four groups that were used to train the model will be referred to as "training groups" while the group that was left out of the regression model will be referred to as the "testing group".

3. Results

Sub-model results yielded a total of sixteen potential predictors to be added to the final model (Appendix, Tables B1–B8). Only sub-model 7 (spatiotemporal variables) did not produce any predictors. Values of all measures are provided in the Appendix (Table A1). Of the final predictors, one term (average internal/external rotation moment during recovery) was correlated to other joint kinetic terms and was therefore removed as a potential predictor. Remaining predictors had VIFs < 3, indicating little to no multicollinearity (Table 2). The 5-fold cross-validation yielded overall model results that were statistically significant (all $P < 0.005$) and on average, explained 47.6% (SD = 3.3%) of the variance in the data (Tjur R^2; Tjur, 2009). The average Tjur R^2 value for the testing groups was 27.3% (SD = 8.1%). Final model coefficients and *P*-values are provided in the Appendix (Tables C1–C5).

Maximum trunk angle and adductor torque were significant predictors of shoulder pain in all of the 5-fold cross-validation models (all $P < 0.03$, Appendix, Tables C1–C5). Positive shoulder joint work during recovery and the adductor torque and average flexion/extension moment during contact interaction were significant predictors in four of the five models ($P < 0.05$ in Models 2–5, and $P < 0.02$ in Models 1, 2, 4 and 5, respectively). CV of the average adduction/abduction moment during contact and CV of the contact angle were significant predictors of shoulder pain in two models ($P < 0.04$ in Models 1 and 5, and $P < 0.03$ in Models 4 and 5, respectively). Finally, the variables that were significant predictors in only one of the models included the negative shoulder joint work during contact ($P = 0.038$, Model 2), the SD of the minimum trunk angle ($P = 0.038$, Model 5), CV of the average radial force ($P = 0.046$, Model 4), the interaction of average tangential force and average flexion/extension moment during contact ($P = 0.035$, Model 4) and the interaction of the average flexion/extension moment during contact and negative shoulder joint work during contact ($P = 0.040$, Model 2).

Regarding these predictors, individuals who developed shoulder pain had more trunk extension, less strength in the shoulder adductors, more positive shoulder joint work during recovery and less negative shoulder joint work during contact. Relative variability was larger for the contact angle, larger for the average adduction/abduction moment during contact and smaller in the average radial force in the P group while absolute variability was smaller for the minimum trunk angle in the P group (Table 3). The first interaction term indicates that as the strength of the shoulder adductors decreases, the influence of the average flexion/extension moment during contact on pain development decreases, which is lower in the individuals who develop pain. The second interaction term indicates that as the average flexion/extension moment during contact decreases, the negative shoulder joint work during contact has more of an influence on pain development, which was smaller in the pain group. The final interaction indicates that as the average tangential force decreases, the influence of the flexion/extension moment during contact on pain development increases, which was lower in those who develop shoulder pain.

4. Discussion

Manual wheelchair users commonly experience shoulder pain and injury, which is often related to rotator cuff impingement or tears

Table 3
Variables that were significant ($P < 0.05$) predictors in at least one model during cross-validation ($n = 102$). Group averages are mean (SD). 'Occurrences' indicates how many of the 5-fold cross-validation models included that predictor. Percent difference is given for all measures excluding relative variability (CVs).

Predictor	Occurrences	No pain group average (n = 74)	Pain group average (n = 28)	% Difference
Individual predictors				
Maximum trunk angle [°]	5	−7.81 (7.32)	−3.55 (8.91)	−74.89
Adductor torque [N-m]	5	71.50 (19.54)	63.90 (20.57)	11.23
Positive shoulder joint work during recovery [mm]	4	3.96 (1.19)	4.11 (1.03)	3.72
CV contact angle [%]	2	4.49 (2.44)	5.31 (2.43)	
CV average add/abd moment during contact [%]	2	131.7 (394.9)	213.2 (544.4)	
CV average F_{rad} [%]	1	16.83 (12.76)	11.27 (5.77)	
SD minimum trunk angle [°]	1	0.841 (0.476)	0.621 (0.336)	30.17
Negative shoulder joint work during contact [mm]	1	−0.486 (0.466)	−0.338 (0.263)	−35.85
Interaction predictors				
Adductor torque [N-m]: Average flex/ext moment during contact [mm]	4			
Average flex/ext moment during contact [mm]: Negative shoulder joint work during contact [mm]	1			
Average F_{tan} [N]: Average flex/ext moment during contact [mm]	1			

(Bayley et al., 1987; Waring and Maynard, 1991). However, the specific causes of shoulder pain development are unknown because most studies examining biomechanical measures between pain and no pain groups are often not longitudinal, but rather examine wheelchair users who presently do and do not have shoulder pain (Collinger et al., 2008; Dysterheft et al., 2017; Jayaraman et al., 2014, 2015, 2016; Moon et al., 2013; Rice et al., 2014). The present study is unique in that at the initial assessment, none of the participants experienced shoulder pain, and were later grouped into P and NP groups based on who developed shoulder pain over the next three years. Categorizing participants based on future pain development allowed for biomechanical measures of strength, kinematics, kinetics and variability to be identified that are important predictors of shoulder pain development. Discussion of these predictors will focus on those that were significant predictors of shoulder pain in at least two of the five final models, as predictors that were only significant in one model may not be generalizable for all MWCU.

4.1. Strength

Strength of the shoulder adductors was a predictor of shoulder pain in all five cross-validation models (Appendix, Tables C1–C5, Models 1–5), with individuals who develop pain having an 11.2% difference in shoulder adductor strength than those who do not. The adductor strength values (Table 3, NP: mean = 1.00 N-m/kg, SD = 0.29 N-m/kg; P: mean = 0.90 N-m/kg, SD = 0.37 N-m/kg) in this study were similar to those found in previous work (Gagnon et al., 2016; Sabick et al., 2004). Our finding that shoulder adductor weakness is predictive of pain is consistent with previous work that found shoulder strength plays a role in shoulder pain development (Mulroy et al., 2015; van Drongelen et al., 2006). The shoulder adductors act to depress the humeral head during weight-bearing tasks such as during transfers (Perry et al., 1996). Therefore, if adductor weakness is present, it may not allow for the required unweighting of the rotator cuff which in turn could cause impingement (Burnham et al., 1993; Mulroy et al., 2015). Therefore, therapies that target shoulder strength, especially in the shoulder adductors, may help decrease the likelihood of shoulder pain development (Curtis et al., 1999; Mulroy et al., 1996), especially when included in rehabilitation programs that address additional factors that contribute to shoulder pain.

4.2. Kinematics

Maximum trunk angle was a significant predictor of shoulder pain in every cross-validation model (Appendix, Tables C1–C5, Models 1–5). The maximum trunk angle for the NP group was more forward leaning than the P group by 4.26° (i.e., in a more flexed position during the entire stroke cycle, both during contact and recovery), yielding a 74.9% difference between groups (Table 3). The population average was similar to previously reported trunk angles (Rao et al., 1996). Maximum trunk angle was not indicative of increased trunk range of motion (Table 4), which may put individuals at higher risk for injury (Rodgers et al., 2000), but rather the NP group had more trunk flexion than the P group for very similar trunk ranges of motion. Future work should analyze how muscle contributions to wheelchair propulsion change with increased trunk flexion without a change in trunk range of motion and determine if these muscle contributions change significantly with only 4–5° of added trunk flexion. In addition, trunk flexion may not be a modifiable risk factor depending on the individual's level of injury. However, we performed a post-hoc analysis and included the subject level of injury as a variable in the sub-models and found it did not correlate with pain, which was consistent with previous work showing that the neurological level of the spinal cord injury was not a predictor of shoulder pain (Mulroy et al., 2015). In addition, average shoulder rotation angle could not be considered as a potential predictor in the final model due to multicollinearity, however it was a significant predictor of shoulder pain ($P = 0.016$) with an overall model $P = 0.013$. Shoulder pathology such as impingement is more likely to occur when internal rotation is paired with abduction or forward flexion (Hawkins and Kennedy, 1980; Neer, 1983; Newsam et al., 1999). Therefore, future work should investigate whether minimizing the shoulder internal rotation angle in addition to increasing trunk flexion can decrease the likelihood of shoulder pain development.

4.3. Kinetics

Consistent with our hypothesis that shoulder joint work would be higher in individuals who develop shoulder pain, the P group had higher positive shoulder joint work during recovery than the NP group. Positive shoulder joint work during recovery was a significant predictor of shoulder pain in four of the five final models (Appendix, Tables C2–C5, Models 2–5). The net work done over the full propulsion cycle (NP: mean = 6.73 N-m, SD = 2.43 N-m; P: mean = 6.45 N-m, SD = 2.40 N-m) was less than that reported in previous work (Guo et al., 2003), most likely because the present study only calculated shoulder joint work rather than the work done by all upper limb segments. Shoulder joint work is positive in the middle of the recovery phase (Fig. 3) when the shoulder delivers power to accelerate the arm backward (Mulroy et al., 1996; Rankin et al., 2011). The P group delivered more power to the shoulder than the NP group in the recovery phase where delivering power is not critically needed (Price et al., 2007; Rankin et al., 2011). This suggests that the NP group conserves power production during the recovery phase in order to conserve upper limb effort that will be needed during contact. However, future work should utilize modeling and simulation to identify the underlying mechanisms that contribute to the differences between positive shoulder joint work during recovery in those who do and do not develop shoulder pain.

The interaction between the adductor torque and average flexion/extension shoulder joint moment during contact was significant in four of the five final models (Appendix, Tables C1–C2, C4–C5, Models 1–2, 4–5). However, the average flexion/extension moment during contact was not a significant predictor of pain on its own or in the final models, and therefore may only be a predictor of pain development for those with lower moments during contact despite stronger shoulder adductor muscles.

4.4. Variability

Adduction moment CV was a predictor of shoulder pain in two of the five final models (Appendix, Tables C1 and C5, Models 1 and 5). However, inconsistent with our hypothesis that individuals who

Table 4
Range of motion, average, maximum and minimum angles for the trunk and shoulder rotation. Values represent mean (SD).

		Range of motion	Average	Maximum	Minimum
Shoulder rotation [°]	No Pain	67.2 (20.6)	53.1 (10.9)	80.6 (10.7)	13.3 (19.1)
	Pain	63.8 (17.3)	60.0 (15.2)	85.7 (13.3)	21.9 (23.3)
Trunk angle [°]	No Pain	5.70 (3.00)	−10.9 (7.62)	−7.81 (7.32)	−13.5 (8.14)
	Pain	5.59 (2.68)	−6.57 (9.48)	−3.55 (8.91)	−9.15 (10.1)

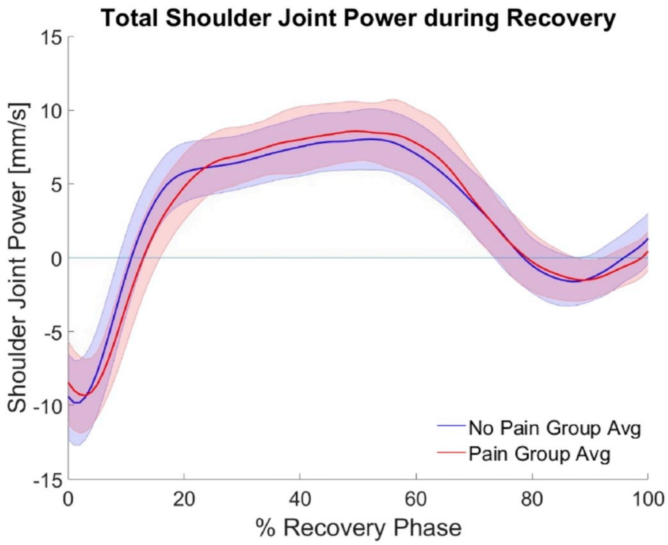

Fig. 3. Total shoulder joint power during the recovery phase with one standard deviation from the mean shaded. Joint power is normalized by body weight (N-mm/N-s).

develop pain would have lower cycle-to-cycle variability, the average adduction/abduction shoulder joint moment during contact CV was higher in the P group. Previous work has found that both handrim (Rice et al., 2014) and joint kinetic (Moon et al., 2013) variability are lower in individuals with shoulder pain. However, variability of shoulder joint moments has not been analyzed for its relationship to shoulder pain in previous work. Thus, the present study shows that kinetic relative variability, while predictive of shoulder pain, should be further analyzed to understand when using increased or decreased cycle-to-cycle relative variability is favorable for preventing shoulder pain.

The contact angle CV in the present study was similar to that reported in previous work (Rice et al., 2014) and was a predictor of pain in two of the five final models (Appendix, Tables C4–C5, Models 4–5). Contrary to our hypothesis, the relative variability of the contact angle was higher in the P group. However, higher contact angle CV for the P group is consistent with previous work that showed structured variability (i.e., sample entropy, SampEn) of the contact angle is higher in individuals with shoulder pain than those without pain (Jayaraman et al., 2016). Higher intra-individual variability in the contact angle, a spatial measure, may also be related to another study that found higher spatial variability of the wrist motion during the beginning of the recovery phase in MWCU who presently have shoulder pain than those without pain (Jayaraman et al., 2014). However, these two variables quantify variability differently and during two different phases of the propulsion cycle, and therefore future work should analyze the relationship between these two measures and also compare methods for quantifying spatial variability (i.e., using CV vs. SampEn).

Another observation to note is that only one absolute variability (SD) measure was a predictor of shoulder pain, but three relative variability (CV) measures were significant predictors. In addition, the CV sub-model had six more predictors than the SD sub-model did, with nearly a 20% increase in the Tjur R^2 value (Appendix, Tables B7 and B8, Sub-models 8 and 9). Thus, relative cycle-to-cycle variability is likely a better predictor of shoulder pain than absolute variability. Finally, higher cycle-to-cycle variability may not prevent shoulder pain development, but rather future work is needed to determine how variability during contact versus recovery in kinematic, kinetic and spatiotemporal measures plays a role in the development of pain in MWCU.

4.5. Limitations

A potential limitation of this study is that the outcome measure, pain, was represented as a binary rather than as a continuous variable. Grouping subjects categorically into pain or no pain groups makes it difficult to see how certain biomechanical measures may influence shoulder pain development more heavily than others. However, because studies have yet to determine definitive predictors for shoulder pain development, using two groups for this study was sufficient in order to determine more generally how MWCU might avoid developing any level of shoulder pain. Future work should look into how these predictors might affect the degree of shoulder pain. Although using categorical groups for pain makes the results of the present study more generalizable, these results may not be generalizable to all MWCU with paraplegia. Another limitation was that the large majority (> 90%) of the population was male. Future work is needed to determine whether the predictors of shoulder pain identified in this study are generalizable to females as well.

In this study, cycle-to-cycle variability was measured over a period of 10 s, which also could be a limitation in that trends of variability may not be detectable in such a short time period. Future work should analyze variability over a longer time period to determine whether these same relationships are observed or if variability changes when considering a longer continuous period of propulsion or multiple trials.

There are other limitations related to the experimental design in that only level propulsion was analyzed and data were measured using a stationary ergometer rather than overground propulsion. MWCU encounter a variety of turns and bouts of propulsion in executing activities of daily living (Sonenblum et al., 2012). However, understanding first how user preferences during level ground propulsion influence pain development is needed before being able to understand the implications of alternative propulsion conditions. Finally, though ergometers do not perfectly replicate overground conditions, trends in kinematic, kinetic and spatiotemporal measures are consistent in MWCU between propulsion using an ergometer and overground propulsion (Koontz et al., 2012), and therefore the conclusions of this study were likely not altered. However, future work should examine how intra-individual variability changes during overground propulsion when compared to an ergometer.

5. Conclusions

This study identified predictors of shoulder pain development in manual wheelchair propulsion by analyzing a population of MWCU who were asymptomatic for shoulder pain at baseline and were categorized into P and NP groups based on who developed shoulder pain at 18 and 36 months later. The most influential predictors of shoulder pain included strength of the shoulder adductors, the maximum trunk angle and the positive shoulder joint work during the recovery phase. In addition, relative cycle-to-cycle variability in kinetic and spatial measures was predictive of shoulder pain, although whether increased or decreased variability was more favorable for avoiding shoulder pain was not consistent. Thus, the predictors identified in this study provide insight for future work to improve the rehabilitation and biomechanical analysis of MWCU, and ultimately decrease their likelihood of developing shoulder pain.

Conflict of interest statement

The authors have no conflict of interest to declare.

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Appendix A

Table A1
Group averages for the NP and P groups for all biomechanical measures excluding SDs and CVs. Group averages are mean (SD).

Predictor			No pain group average (n = 74)	Pain group average (n = 28)	% Difference
Strength measures					
Flexion torque [N-m]			61.24 (17.40)	57.88 (18.94)	5.65
Adduction torque [N-m]			71.50 (19.54)	63.90 (20.57)	11.23
External rotation torque [N-m]			34.03 (9.55)	32.16 (10.95)	5.66
Kinematics					
Trunk angle [°]		RoM	5.70 (3.00)	5.59 (2.68)	1.79
		Average	−10.86 (7.62)	−6.57 (9.48)	−49.17
		Minimum	−13.50 (8.14)	−9.15 (10.05)	−38.45
		Maximum	−7.81 (7.32)	−3.55 (8.91)	−74.89
Plane-of-elevation [°]		RoM	76.27 (21.72)	70.10 (20.67)	8.43
		Average	−26.65 (11.35)	−29.44 (10.57)	−9.95
		Minimum	−57.13 (10.09)	−56.95 (10.26)	−0.316
		Maximum	19.14 (20.10)	13.15 (20.61)	37.09
Elevation angle [°]		RoM	25.07 (7.34)	28.19 (8.32)	11.72
		Average	40.18 (6.62)	41.27 (5.13)	2.67
		Minimum	27.56 (7.04)	26.76 (4.71)	2.95
		Maximum	52.63 (7.61)	54.95 (7.57)	4.31
Shoulder rotation [°]		RoM	67.24 (20.58)	63.79 (17.34)	5.26
		Average	53.10 (10.90)	59.98 (15.21)	12.18
		Minimum	13.34 (19.12)	21.87 (23.27)	48.44
		Maximum	80.58 (10.65)	85.66 (13.33)	6.11
Handrim kinetics					
Tangential force [N]		Average	19.48 (4.86)	18.35 (4.55)	5.93
		Maximum	32.39 (9.58)	29.69 (8.28)	8.69
Radial force [N]		Average	−16.29 (6.33)	−18.57 (5.88)	−13.09
		Minimum	−30.65 (10.30)	−33.12 (11.66)	−7.75
Lateral force [N]		Average	−4.84 (3.48)	−5.62 (3.53)	−14.95
		Minimum	−9.61 (4.56)	−10.09 (4.62)	−4.93
		Maximum	1.59 (2.03)	1.31 (0.942)	19.37
Total force [N]		Average	28.05 (6.52)	28.45 (7.08)	1.41
		Maximum	42.87 (12.05)	41.91 (12.85)	2.27
Joint kinetics					
Flexion/extension moment [mm]	Avg.	Contact	7.69 (3.55)	7.13 (3.06)	7.54
		Recovery	−2.32 (1.49)	−2.18 (1.58)	−5.99
		Full cycle	2.69 (1.93)	2.48 (1.78)	8.23
	Peak	Contact	14.30 (5.79)	13.06 (4.89)	9.03
		Recovery	3.51 (2.44)	3.42 (2.31)	2.59
		Full cycle	14.30 (5.78)	13.06 (4.89)	9.03
Adduction/abduction moment [mm]	Avg.	Contact	1.38 (3.50)	2.01 (3.05)	36.76
		Recovery	−6.03 (1.02)	−6.34 (0.967)	−5.04
		Full cycle	−2.32 (1.91)	−2.17 (1.75)	−6.94
	Peak	Contact	6.36 (5.17)	6.71 (4.23)	5.30
		Recovery	−3.05 (1.21)	−3.09 (1.19)	−1.35
		Full cycle	6.40 (5.10)	6.72 (4.17)	5.00
Internal/external rotation moment [mm]	Avg.	Contact	5.84 (2.21)	5.59 (1.64)	4.28
		Recovery	−1.38 (0.968)	−0.859 (0.994)	−46.84
		Full cycle	2.23 (1.22)	2.37 (0.916)	6.08
	Peak	Contact	9.67 (3.74)	8.86 (2.79)	8.75
		Recovery	4.06 (2.00)	4.54 (2.13)	11.20
		Full cycle	9.68 (3.72)	8.90 (2.77)	8.41
Positive shoulder joint work [mm]		Contact	7.35 (3.82)	6.45 (2.84)	13.10
		Recovery	3.96 (1.19)	4.11 (1.03)	3.72
		Full cycle	11.31 (4.28)	10.55 (3.51)	6.90
Negative shoulder joint work [mm]		Contact	−0.486 (0.466)	−0.338 (0.263)	−35.85
		Recovery	−1.16 (0.659)	−1.31 (0.829)	−12.77
		Full cycle	−1.64 (0.847)	−1.65 (0.913)	−0.514
Spatiotemporal measures					
Contact time [s]			0.444 (0.105)	0.460 (0.099)	3.57
Release time [s]			0.716 (0.199)	0.716 (0.152)	0.119
Cycle time [s]			1.16 (0.267)	1.18 (0.228)	1.31
Cadence [Hz]			0.907 (0.207)	0.882 (0.170)	2.80
Contact percentage [%]			0.387 (0.056)	0.393 (0.045)	1.57
Start angle [°]			−29.12 (9.79)	−30.77 (8.66)	−5.53
End angle [°]			48.56 (10.88)	46.02 (10.89)	5.38
Contact angle [°]			77.68 (12.84)	76.79 (14.83)	1.15
NRT [m]			−0.019 (0.053)	−0.017 (0.057)	−7.41
TRT [m]			0.046 (0.038)	0.049 (0.036)	5.16
NRT/TRT			0.044 (0.887)	0.091 (0.914)	70.40

Table B1
Sub-model 1 results. Potential predictors included strength measures with collinear terms removed. All predictors with $P < 0.1$ were added to the final model. Tjur $R^2 = 3.0\%$, overall model $P = 0.082$.

Strength		
	Predictor	*P*-value
	Intercept	0.640
1	Adductor Torque [N-m]	0.090

Table B2
Sub-model 2 results. Potential predictors included handrim kinetics with collinear terms removed. All predictors with $P < 0.1$ were added to the final model. Tjur $R^2 = 5.3\%$, overall model $P = 0.055$.

Handrim kinetics		
	Predictor	*P*-value
	Intercept	0.493
1	Average F_{tan} [N]	0.093
2	Average F_{rad} [N]	0.040

Table B3
Sub-model 3 results. Potential predictors included joint kinetics with collinear terms removed. All predictors with $P < 0.1$ were added to the final model. Tjur $R^2 = 9.2\%$, overall model $P = 0.012$.

Joint kinetics		
	Predictor	*P*-value
	Intercept	0.069
1	Average adduction/abduction moment during recovery [mm]	0.096
2	Average internal/external rotation moment during recovery [mm]	0.013

Table B4
Sub-model 4 results. Potential predictors included handrim and joint kinetics with collinear terms removed. All predictors with $P < 0.1$ were added to the final model. Tjur $R^2 = 22.5\%$, overall model $P < 0.001$.

All kinetics		
	Predictor	*P*-value
	Intercept	0.028
1	Average F_{rad} [N]	0.004
2	Average flexion/extension moment during contact [mm]	0.019
3	Average internal/external rotation moment during recovery [mm]	0.002
4	Negative shoulder joint work during contact [mm]	0.018
5	Positive shoulder joint work during recovery [mm]	0.007

Table B5
Sub-model 5 results. Potential predictors included handrim kinetics, joint kinetics and strength measures with collinear terms removed. All predictors with $P < 0.1$ are indicated using '*' and were added to the final model. Tjur $R^2 = 35.4\%$, overall model $P < 0.001$.

All kinetics + strength		
	Predictor	*P*-value
	Intercept	0.993
1	Adductor torque [N-m]	0.005*
2	Average F_{tan} [N]	0.080*

(*continued on next page*)

Table B5 (*continued*)

All kinetics + strength		
	Predictor	*P*-value
3	Average F_{rad} [N]	0.008*
4	Average flexion/extension moment during contact [mm]	0.547
5	Average internal/external rotation moment during recovery [mm]	0.001*
6	Negative shoulder joint work during contact [mm]	0.032*
7	Positive shoulder joint work during recovery [mm]	0.006*
8	Adductor torque: Average flexion/extension moment during contact interaction	0.010*
9	Average F_{tan}: Average flexion/extension moment during contact interaction	0.031*
10	Average flexion/extension moment during contact: Negative shoulder joint work during contact interaction	0.080*

Table B6
Sub-model 6 results. Potential predictors included shoulder and trunk kinematics with collinear terms removed. All predictors with $P < 0.1$ were added to the final model. Tjur $R^2 = 6.0\%$, overall model $P = 0.016$.

Kinematics		
	Predictor	*P*-value
	Intercept	0.034
1	Maximum trunk angle [°]	0.019

Table B7
Sub-model 8 results. Potential predictors included SDs with collinear terms removed. All predictors with $P < 0.1$ were added to the final model. Tjur $R^2 = 5.0\%$, overall model $P = 0.018$.

SDs		
	Predictor	*P*-value
	Intercept	0.980
1	SD minimum trunk angle [°]	0.032

Table B8
Sub-model 9 results. Potential predictors included CVs with collinear terms removed. All predictors with $P < 0.1$ are indicated using '*' and were added to the final model. Tjur $R^2 = 24.9\%$, overall model $P < 0.001$.

CVs		
	Predictor	*P*-value
	Intercept	0.617
1	CV minimum shoulder rotation [%]	0.144
2	CV average F_{tan} [%]	0.033*
3	CV average F_{rad} [%]	0.002*
4	CV contact angle [%]	0.037*
5	CV average adduction/abduction moment during contact [%]	0.096*
6	CV average adduction/abduction moment during recovery [%]	0.118
7	CV average flexion/extension moment over full cycle [%]	0.109

Table C1
Final model values for Model 1 of the 5-fold cross validation procedure. Groups 1–4 ($n = 81$) were used to train the model. "*" indicates a significant correlation ($P < 0.05$). "†" indicates approaching significance ($P < 0.1$).

Final predictor	β-Estimate	*P*-value	No pain group average ($n = 58$)	Pain group average ($n = 23$)
Intercept	6.905	0.346		
Adductor torque [N-m]	−0.145	0.014*	73.57 (19.41)	62.57 (19.11)
Maximum trunk angle [°]	0.187	0.011*	−7.78 (7.53)	−3.74 (9.22)

(*continued on next page*)

Table C1 (*continued*)

Final predictor	β-Estimate	*P*-value	No pain group average (*n* = 58)	Pain group average (*n* = 23)
Average F_{tan} [N]	0.251	0.393	19.64 (4.66)	18.13 (4.19)
Average F_{rad} [N]	−0.093	0.280	−15.99 (5.91)	−19.03 (5.60)
Average flex/ext moment during contact [mm]	−0.401	0.634	7.85 (3.58)	7.35 (3.09)
Average ab/adduction moment during recovery [mm]	0.423	0.407	−5.99 (1.03)	−6.19 (0.894)
Negative shoulder joint work during contact [mm]	4.376	0.185	−0.482 (0.475)	−0.319 (0.245)
Positive shoulder joint work during recovery [mm]	1.017	0.064†	3.96 (1.27)	3.94 (0.866)
SD minimum trunk angle [°]	−2.184	0.105	0.881 (0.485)	0.600 (0.316)
CV average F_{tan} [%]	−0.037	0.637	12.58 (5.50)	12.06 (4.80)
CV average F_{rad} [%]	−0.137	0.105	17.86 (13.76)	10.19 (3.83)
CV average ab/adduction moment during contact [%]	0.003	0.037*	151.2 (444.5)	252.5 (595.6)
CV contact angle [%]	0.286	0.215	4.64 (2.58)	5.12 (2.08)
Adductor torque [N-m]: Average flex/ext moment during contact [mm]	0.018	0.016*		
Average F_{tan} [N]: Average flex/ext moment during contact [mm]	−0.060	0.145		
Average flex/ext moment during contact [mm]: Negative shoulder joint work during contact [mm]	−0.497	0.159		
Overall model		1.13E−4		
		Tjur R^2		
Training group (Groups 1–4)		49.5%		
Test group (Group 5)		15.6%		

Table C2

Final model values for Model 2 of the 5-fold cross validation procedure. Groups 1–3, 5 (*n* = 82) were used to train the model. "*" indicates a significant correlation ($P < 0.05$). "†" indicates approaching significance ($P < 0.1$).

Final predictor	β-Estimate	*P*-value	No pain group average (*n* = 60)	Pain group average (*n* = 22)
Intercept	3.140	0.632		
Adductor torque [N-m]	−0.176	0.012*	71.20 (20.22)	66.20 (20.41)
Maximum trunk angle [°]	0.190	0.008*	−8.04 (7.37)	−2.77 (9.29)
Average F_{tan} [N]	0.367	0.225	19.44 (4.88)	18.72 (4.39)
Average F_{rad} [N]	−0.128	0.123	−16.24 (6.33)	−18.71 (6.20)
Average flex/ext moment during contact [mm]	−0.989	0.156	7.59 (3.51)	7.15 (3.01)
Average ab/adduction moment during recovery [mm]	0.183	0.721	−6.01 (1.03)	−6.41 (0.962)
Negative shoulder joint work during contact [mm]	12.427	0.038*	−0.458 (0.440)	−0.308 (0.247)
Positive shoulder joint work during recovery [mm]	1.645	0.010*	3.94 (1.16)	4.10 (1.10)
SD minimum trunk angle [°]	−0.776	0.465	0.812 (0.468)	0.651 (0.357)
CV average F_{tan} [%]	0.070	0.326	11.83 (5.54)	11.80 (5.08)
CV average F_{rad} [%]	−0.126	0.079†	16.03 (11.26)	11.98 (6.10)
CV average ab/adduction moment during contact [%]	0.003	0.100	95.16 (167.4)	258.1 (609.2)
CV contact angle [%]	0.322	0.136	4.50 (2.51)	5.30 (2.61)
Adductor torque [N-m]: Average flex/ext moment during contact [mm]	0.023	0.014*		
Average F_{tan} [N]: Average flex/ext moment during contact [mm]	−0.071	0.125		
Average flex/ext moment during contact [mm]: Negative shoulder joint work during contact [mm]	−1.428	0.040*		
Overall model		2.64E−4		
		Tjur R^2		
Training group (Groups 1–3, 5)		47.5%		
Test group (Group 4)		29.4%		

Table C3

Final model values for Model 3 of the 5-fold cross validation procedure. Groups 1–2, 4–5 (*n* = 81) were used to train the model. "*" indicates a significant correlation ($P < 0.05$). "†" indicates approaching significance ($P < 0.1$).

Final predictor	β-Estimate	*P*-value	No pain group average (*n* = 62)	Pain group average (*n* = 19)
Intercept	0.411	0.953		
Adductor torque [N-m]	−0.151	0.024*	72.95 (19.04)	58.24 (20.74)
Maximum trunk angle [°]	0.217	0.007*	−8.13 (7.42)	−4.30 (8.75)
Average F_{tan} [N]	0.450	0.130	19.33 (5.04)	18.39 (4.59)
Average F_{rad} [N]	−0.100	0.196	−16.20 (6.63)	−18.49 (6.46)
Average flex/ext moment during contact [mm]	−0.306	0.637	7.60 (3.71)	7.16 (3.29)
Average ab/adduction moment during recovery [mm]	0.004	0.994	−6.02 (0.950)	−6.53 (0.913)
Negative shoulder joint work during contact [mm]	6.293	0.062†	−0.493 (0.479)	−0.404 (0.262)
Positive shoulder joint work during recovery [mm]	1.002	0.048*	4.02 (1.21)	4.22 (1.02)
SD minimum trunk angle [°]	−1.103	0.367	0.818 (0.488)	0.675 (0.365)
CV average F_{tan} [%]	0.054	0.494	11.75 (5.46)	12.27 (5.67)
CV average F_{rad} [%]	−0.086	0.246	16.61 (13.11)	11.35 (6.56)

(*continued on next page*)

Table C3 (*continued*)

Final predictor	β-Estimate	*P*-value	No pain group average (*n* = 62)	Pain group average (*n* = 19)
CV average ab/adduction moment during contact [%]	0.002	0.058†	120.9 (405.2)	226.2 (613.7)
CV contact angle [%]	0.236	0.292	4.62 (2.50)	5.23 (2.40)
Adductor torque [N-m]: Average flex/ext moment during contact [mm]	0.016	0.058†		
Average F_{tan} [N]: Average flex/ext moment during contact [mm]	−0.070	0.103		
Average flex/ext moment during contact [mm]: Negative shoulder joint work during contact [mm]	−0.698	0.058†		
Overall model		2.05E−3		
		Tjur R^2		
Training group (Groups 1–2, 4–5)		41.8%		
Test group (Group 3)		39.7%		

Table C4

Final model values for Model 4 of the 5-fold cross validation procedure. Groups 1, 3–5 (*n* = 82) were used to train the model. "*" indicates a significant correlation ($P < 0.05$). "†" indicates approaching significance ($P < 0.1$).

Final predictor	β-Estimate	*P*-value	No pain group average (*n* = 57)	Pain group average (*n* = 25)
Intercept	5.250	0.463		
Adductor torque [N-m]	−0.206	0.007*	69.20 (18.49)	64.47 (21.64)
Maximum trunk angle [°]	0.150	0.027*	−7.70 (6.49)	−3.91 (8.30)
Average F_{tan} [N]	0.462	0.131	19.60 (5.03)	17.95 (4.65)
Average F_{rad} [N]	−0.012	0.920	−16.64 (6.11)	−17.78 (5.05)
Average flex/ext moment during contact [mm]	−0.774	0.303	7.55 (3.35)	6.70 (2.68)
Average ab/adduction moment during recovery [mm]	0.187	0.708	−6.04 (1.06)	−6.30 (1.01)
Negative shoulder joint work during contact [mm]	3.572	0.274	−0.508 (0.468)	−0.318 (0.268)
Positive shoulder joint work during recovery [mm]	1.130	0.029*	4.02 (1.15)	4.08 (1.06)
SD minimum trunk angle [°]	−1.394	0.265	0.859 (0.488)	0.612 (0.340)
CV average F_{tan} [%]	0.008	0.907	12.45 (5.83)	12.48 (5.01)
CV average F_{rad} [%]	−0.222	0.046*	17.38 (13.04)	11.34 (6.02)
CV average ab/adduction moment during contact [%]	0.004	0.069†	144.9 (446.8)	120.61 (244.7)
CV contact angle [%]	0.590	0.018*	4.39 (2.44)	5.38 (2.53)
Adductor torque [N-m]: Average flex/ext moment during contact [mm]	0.033	0.004*		
Average F_{tan} [N]: Average flex/ext moment during contact [mm]	−0.096	0.035*		
Average flex/ext moment during contact [mm]: Negative shoulder joint work during contact [mm]	−0.390	0.312		
Overall model		3.03E−5		
		Tjur R^2		
Training group (Groups 1, 3–5)		51.7%		
Test group (Group 2)		22.4%		

Table C5

Final model values for Model 5 of the 5-fold cross validation procedure. Groups 2–5 (*n* = 82) were used to train the model. "*" indicates a significant correlation ($P < 0.05$). "†" indicates approaching significance ($P < 0.1$).

Final predictor	β-Estimate	*P*-value	No pain group average (*n* = 59)	Pain group average (*n* = 23)
Intercept	1.892	0.772		
Adductor torque [N-m]	−0.187	0.029*	70.47 (20.28)	67.07 (20.14)
Maximum trunk angle [°]	0.231	0.003*	−7.36 (7.72)	−3.11 (9.12)
Average F_{tan} [N]	0.639	0.153	19.38 (4.70)	18.64 (4.96)
Average F_{rad} [N]	−0.131	0.125	−16.40 (6.62)	−18.91 (6.20)
Average flex/ext moment during contact [mm]	−0.439	0.490	7.88 (3.61)	7.36 (3.30)
Average ab/adduction moment during recovery [mm]	0.476	0.365	−6.10 (1.04)	−6.34 (1.03)
Negative shoulder joint work during contact [mm]	6.764	0.154	−0.489 (0.469)	−0.355 (0.285)
Positive shoulder joint work during recovery [mm]	1.324	0.017*	3.84 (1.17)	4.20 (1.09)
SD minimum trunk angle [°]	−3.306	0.038*	0.839 (0.452)	0.577 (0.304)
CV average F_{tan} [%]	−0.034	0.792	11.83 (4.83)	11.88 (4.41)
CV average F_{rad} [%]	−0.063	0.429	16.33 (12.58)	11.55 (6.07)
CV average ab/adduction moment during contact [%]	0.002	0.025*	148.1 (441.2)	220.8 (599.3)
CV contact angle [%]	0.481	0.023*	4.32 (2.15)	5.50 (2.52)
Adductor torque [N-m]: Average flex/ext moment during contact [mm]	0.024	0.017*		
Average F_{tan} [N]: Average flex/ext moment during contact [mm]	−0.092	0.086†		
Average flex/ext moment during contact [mm]: Negative shoulder joint work during contact [mm]	−0.744	0.141		
Overall model		1.67E−4		
		Tjur R^2		
Training group (Groups 2–5)		47.6%		
Test group (Group 1)		29.7%		

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