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The relationship between the hand pattern used during fast wheelchair propulsion and shoulder pain development

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ABSTRACT

Up to 84% of manual wheelchair users (MWCU) with spinal cord injury experience shoulder pain, which is correlated with shoulder adductor weakness in this population. Modeling studies have shown weak shoulder adductors lead to compensations from the deltoid and rotator cuff muscles during propulsion, which may lead to altered propulsion mechanics. However, the role recovery phase hand pattern has in pain development is unclear, as each hand pattern is associated with unique mechanics and different levels of muscle demand. Previous research found no correlation between hand pattern and shoulder pain at self-selected speeds. However, fast propulsion may exacerbate poor mechanics caused by shoulder muscle weakness, which may reveal those at risk for pain development. The present study evaluated whether the hand pattern used during fast wheelchair propulsion is correlated with shoulder pain. We also assessed whether shoulder adductor strength was correlated with hand pattern. Fast propulsion data from two subsets of MWCU were analyzed at three time points (baseline, 18 months, 36 months). All participants were pain-free at baseline. Subset 1 compared individuals who remained pain-free to those who developed shoulder pain. Subset 2 compared individuals with chronic pain at follow-up to those whose pain resolved over time. The hand pattern used was not different between groups in either subset. However, more over-rim patterns were correlated with lower adductor strength in Subset 1. These results suggest that although the hand pattern used during fast propulsion is not correlated with shoulder pain, more over-rim hand patterns may indicate weaker shoulder adductors.

1. Introduction

The majority of manual wheelchair users (MWCU) with spinal cord injury experience shoulder pain due to the repetitive demand on the upper limbs, with studies reporting prevalence from 60% to 84% (e.g., Brose et al., 2008; Kentar et al., 2018). The recovery phase hand pattern used by MWCU influences upper extremity demand during wheelchair propulsion, and therefore may be related to shoulder pain. There are four hand patterns commonly used by MWCU (Fig. 1). Recent modeling work simulating these hand patterns found that the semi-circular (SC) and double-loop (DL) hand patterns require the least overall muscle demand compared to the single-loop (SL) and arcing (ARC) patterns (Slowik et al., 2016b). Furthermore, compared to the under-rim patterns (SC and DL), the SL pattern is typically associated with a higher cadence (Boninger et al., 2002; Kwarciak et al., 2012), lower push percentage (Boninger et al., 2002), smaller contact angle and higher braking moment (Kwarciak et al., 2012), which are considered risk-factors for shoulder pain development (Paralyzed Veterans of America Consortium for Spinal Cord Medicine, 2005). Therefore, we would expect that the SL pattern is correlated with shoulder pain due to its higher muscle demand and associated propulsion mechanics.

Shoulder muscle weakness is a predictor of shoulder pain in MWCU (van Drongelen et al., 2006), specifically weakness in the shoulder adductors (Mulroy et al., 2015). In addition, weakness in the shoulder adductors relative to the abductors can put individuals at risk for pain development (e.g., Burnham et al., 1993; Wilbanks and Bickel, 2016). Previous modeling work has provided insight into the muscle power and stress compensations that occur when the primary shoulder adductors (pectoralis major and latis-

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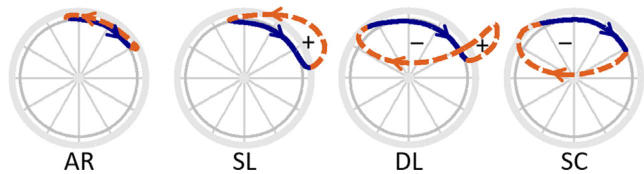

Fig. 1. The four common hand patterns: arcing (ARC), single-loop (SL), double-loop (DL) and semi-circular (SC). Positive and negative signs indicate the signed area used in calculating net radial thickness (NRT) for each pattern (Slowik et al., 2015).

simus dorsi) are weakened individually (Slowik et al., 2016a). This work suggests that with weakened adductors, the primary rotator cuff muscles (infraspinatus, supraspinatus and subscapularis) have the greatest increases in muscle stress (Slowik et al., 2016a) as they act to pull the humeral head downward and prevent shoulder impingement (van Drongelen et al., 2006). In addition, weakening the pectoralis major results in increased power from the anterior deltoid, and weakening the latissimus dorsi results in increased power from the middle deltoid and pectoralis major (Slowik et al., 2016a). Weakness or fatigue of the shoulder adductors and the associated compensatory muscle patterns used could be reflected in altered propulsion mechanics and consequently, the choice of hand pattern. Compared to the other patterns, the DL pattern requires increased anterior deltoid power but uses lower pectoralis major muscle power and the lowest total muscle power. On the other hand, the SL pattern requires the highest middle deltoid muscle power compared to the other patterns as well as the highest infraspinatus and subscapularis muscle stress and the second-highest supraspinatus muscle stress (Slowik et al., 2016b). Therefore, because of the high middle deltoid power and high muscle stress in the rotator cuff associated with the SL pattern, we would expect that the SL pattern is also correlated with weakness in the shoulder adductors.

Although previous analysis of hand patterns found no correlation with future shoulder pain development (Walford et al., 2019) this may have been due to only evaluating propulsion at self-selected speeds. During fast wheelchair propulsion, individuals may display poor propulsion mechanics that are not typically identifiable during self-selected conditions due to the increased mechanical demands associated with the movement. Indeed, previous work has demonstrated that propelling a wheelchair at higher speeds increases the load on the upper limb muscles and joints (Collinger et al., 2008; Koontz et al., 2002; Kulig et al., 1998; Qi et al., 2019, 2012), which may elicit alternative biomechanical strategies if shoulder weakness is present. Thus, examining fast propulsion mechanics may help identify individuals who are at risk for shoulder pain development.

The primary aim of this study was to determine whether the hand pattern used during fast wheelchair propulsion is correlated with shoulder pain development in MWCU with a spinal cord injury. A secondary aim was to determine whether shoulder adductor strength is correlated with the hand pattern used during fast propulsion. We hypothesize that 1) individuals who develop shoulder pain use more over-rim (e.g., SL) hand patterns, and 2) individuals with current shoulder pain who continue to have pain use more over-rim patterns than those whose pain resolves over time. We also expect that 3) weaker shoulder adductors are correlated with more over-rim patterns, regardless of whether shoulder pain is currently present. Identifying specific hand patterns associated with shoulder muscle weakness and pain development would provide clinicians a clear benchmark to identify individuals who may benefit from shoulder-strengthening exercises or training in less potentially injurious hand patterns in order to prevent future shoulder pain development.

2. Methods

2.1. Subjects

Experimental data from a previously collected dataset were analyzed (Mulroy et al., 2015). Individuals with paraplegia who were between 2 and 20 years post spinal cord injury were recruited from outpatient clinics at Rancho Los Amigos National Rehabilitation Center and gave informed consent in accordance with the Institutional Review Board. Data were collected at three time points: baseline, 18 months after baseline and 36 months after baseline. Participants were asymptomatic for shoulder pain at the baseline data collection with a total score on the Wheelchair User's Shoulder Pain Index (WUSPI; Curtis et al., 1995) of $\leq$ 12. Individuals were classified as having developed shoulder pain at the 18-month and 36-month follow-up assessments if they experienced an increase of $\geq$ 10 points from baseline on the WUSPI (e.g., Curtis and Black, 1999). Two subsets of individuals were selected for this analysis. Participants in the first subset were pain-free at the baseline and 18-month time points and were divided into pain ($N = 19$) and no pain ($N = 41$) groups based on whether shoulder pain had developed at the 36-month time point (Table 1). Individuals in the second subset were pain-free at baseline and had shoulder pain at 18-months, with participants divided into chronic pain (pain continued at 36 months) ($N = 12$) and pain resolved ($N = 13$) groups based on their change in shoulder pain at the 36-month time point (Table 2). Specifically, the chronic pain group had an increase in pain scores $\geq$ 10 points from baseline at both 18 and 36 months (pain at both times), while the pain resolved group had 36-month pain scores that had fallen within 10 points of their baseline pain score (pain at 18 months, no pain at 36 months). All participants were required to have at least three complete fast speed propulsion cycles for two of the three data collection sessions and pain scores for all three time points.

2.2. Data collection

Strength, kinetic and kinematic data were collected from the participants at baseline, and then 18 months and 36 months after baseline. Participants propelled their own wheelchair on a stationary ergometer with the resistance set to emulate overground propulsion on a tile surface (Requejo et al., 2015) at their fastest comfortable speed (Tables 1-2). Participants were given a trial of fast propulsion of up to 30s for accommodation followed by one to two minutes of rest to prevent fatigue. After the rest period, data collection occurred during the last 10s of a 15-second trial. Kinematic data were collected from the wheel, trunk and upper extremities using a CODA motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK) at 100 Hz. Fifteen active markers were placed on body segment landmarks and the right wheel (e.g., Lighthall-Haubert et al., 2009). Three-dimensional kinetic data were collected from the right handrim at 200 Hz using an instrumented wheel (SmartWheel; Out-Front, Pasco, WA, USA). To assess shoulder strength, peak maximal isometric torque of the shoulder flexors, extensors, abductors, adductors, internal rotators and external rotators were collected using a Biodex System 3 Pro dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA). These measurements were collected with subjects' trunk and pelvis constrained (e.g., Mulroy et al., 2015), and were normalized by the individual's bodyweight.

2.3. Data processing

Kinematic and kinetic data were processed in Visual 3D (C-Motion, Inc., Germantown, MD, USA) using a low-pass, fourth-

Table 1
Subject demographics for the first subset. The group height and standard deviations did not change at 18 and 36 months, and therefore were not included. All values are mean ± one standard deviation.

		No Pain (N = 41)	Pain at 36 months (N = 19)	All (N = 60)
Baseline	Men/Women	39/2	17/2	
	Age (years)	35.9 ± 7.58	35.7 ± 9.68	35.9 ± 8.31
	Time since injury (years)	10.5 ± 5.74	9.29 ± 6.01	10.1 ± 5.86
	Height (m)	1.74 ± 0.10	1.74 ± 0.09	1.74 ± 0.10
	Mass (kg)	77.0 ± 17.1	76.4 ± 13.4	76.8 ± 16.0
	Speed (m/s)	1.59 ± 0.33	1.46 ± 0.35	1.56 ± 0.34
	Pain (Y/N)	N	N	
18-months	Mass (kg)	77.6 ± 16.9	74.5 ± 15.8	76.6 ± 16.6
	Speed (m/s)	1.50 ± 0.30	1.46 ± 0.30	1.49 ± 0.30
	Pain (Y/N)	N	N	
36-months	Mass (kg)	78.8 ± 18.8	75.0 ± 18.0	77.8 ± 18.7
	Speed (m/s)	1.50 ± 0.28	1.48 ± 0.28	1.49 ± 0.28
	Pain (Y/N)	N	Y	

Table 2
Subject demographics for the second subset. Baseline data were not analyzed in this subset. Height group averages and standard deviations did not change at 36 months and therefore are not included. All values are mean ± one standard deviation.

		Chronic Pain at 18 and 36 months (N = 12)	Pain Resolved at 36 months (N = 13)	All (N = 25)
18-months	Men/Women	11/1	11/2	
	Age (years)	34.8 ± 8.78	40.6 ± 8.30	37.8 ± 9.02
	Time since injury (years)	6.27 ± 4.44	12.4 ± 6.66	9.45 ± 6.47
	Height (m)	1.73 ± 0.08	1.73 ± 0.12	1.73 ± 0.10
	Mass (kg)	74.3 ± 23.2	78.6 ± 20.0	76.6 ± 21.6
	Speed (m/s)	1.47 ± 0.30	1.48 ± 0.38	1.47 ± 0.34
	Pain (Y/N)	Y	Y	
36-months	Mass (kg)	72.3 ± 20.8	77.4 ± 17.5	74.9 ± 19.8
	Speed (m/s)	1.49 ± 0.31	1.45 ± 0.37	1.47 ± 0.35
	Pain (Y/N)	Y	N	

order, zero-lag Butterworth filter with cutoff frequencies of 6 and 10 Hz, respectively. A threshold of 1 Nm for the moment about the wheel was used to determine the beginning and end of the push and recovery phases. The third metacarpophalangeal joint center (MCP3) was located using a method described previously (Rao et al., 1996), and the path of the MCP3 was projected onto the handrim plane and averaged across cycles for each subject using custom Matlab (Mathworks Inc., Natick, MA, USA) code. 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 (Slowik et al., 2015). A positive NRT value indicates a primarily over-rim pattern (e.g., SL) and a negative NRT value indicates an under-rim hand pattern (e.g., SC). Small TRT values indicate the hand pattern stays near the handrim (e.g., ARC), and greater TRT values indicate the hand pattern moves farther away from the handrim (Fig. 1). To simplify the analyses, the hand pattern, strength data and pain scores from only the right upper extremity were analyzed. In the first subset, those who developed pain at the 36-month data collection (pain group) were compared to those who did not experience pain at any time point (no pain group) in order to assess whether hand pattern or strength influenced the development of pain well before pain was present. In the second subset, the participants' baseline data were not analyzed so that the comparisons could be made between individuals with shoulder pain at 18 months who would either continue to have pain later (chronic pain group) or those who no longer had pain present at 36 months (pain resolved group).

2.4. Statistical analyses

To test our first and second hypotheses, NRT and TRT were compared between the pain and no pain groups (first subset) and the chronic pain and pain resolved at 36 months groups (second subset), respectively, to determine if the hand pattern used was related to shoulder pain over time. NRT and TRT were compared between groups using two linear mixed-effects models for each subset (R Core Team, 2018). NRT (or TRT) was the dependent variable, the fixed factors included group (subset 1: pain or no pain; subset 2: chronic pain or pain resolved), time point (subset 1: baseline, 18 or 36; subset 2: time from injury at 18 months, time from injury at 36 months) and their interaction, and the random factor was subject. The models for subset 2 included time since injury as a fixed factor instead of time point because the group averages for time since injury were relatively different (Table 2). To test our third hypothesis, an additional model was created for each subset to determine if weakness in the shoulder adductors was correlated to the use of a more over-rim pattern. In this model, the dependent variable was NRT, the fixed factor was adduction strength and the random factor was subject. Significance was defined as $\alpha = 0.05$.

3. Results

3.1. Subset 1: No pain versus pain at 36 months

There was a trend for the pain group to use a more over-rim pattern (e.g., SL) than the no pain group (Fig. 2), however there were no significant differences between the pain group and no pain group for either NRT or TRT (all $p > 0.05$) at any time point (Table 3). Higher NRT values (more over-rim area) were significantly correlated with lower shoulder adduction strength ($p = 0.042$, marginal $R^2 = 0.019$).

3.2. Subset 2: Chronic pain (at both 18 and 36 months) versus pain resolved

There were no differences in NRT or TRT between individuals whose shoulder pain at 18 months continued (chronic pain) or resolved at 36 months (pain resolved) (Fig. 3, all $p > 0.05$). Higher

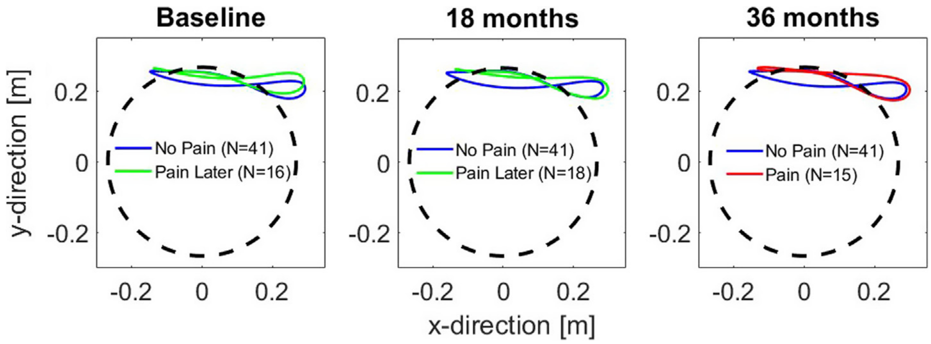

Fig. 2. Hand patterns across time for the No Pain (blue) and Pain (green = pre-pain, red = pain present) groups. Individuals in the pain group (total N = 19) were excluded from a time point when they were missing motion data from that time point. All subjects have data for at least two of the three time points and pain scores for every time point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Net radial thickness (NRT) and total radial thickness (TRT) of the hand pattern during fast wheelchair propulsion for each time point. All values are mean ± one standard deviation.

		No Pain	Pain at 36 months	All
NRT [m]	Baseline	0.000 ± 0.065	0.018 ± 0.061	0.005 ± 0.064
	18-months	−0.009 ± 0.064	0.013 ± 0.060	−0.002 ± 0.063
	36-months	−0.008 ± 0.067	0.032 ± 0.038	0.003 ± 0.063
TRT [m]	Baseline	0.065 ± 0.043	0.059 ± 0.036	0.063 ± 0.041
	18-months	0.069 ± 0.042	0.064 ± 0.042	0.064 ± 0.042
	36-months	0.067 ± 0.040	0.044 ± 0.028	0.061 ± 0.038

NRT values were not significantly correlated with lower shoulder adductor strength ($p > 0.05$).

4. Discussion

The aim of this study was to determine whether the hand pattern used during fast wheelchair propulsion is correlated with shoulder pain development over time, and whether shoulder adductor weakness correlates to the use of a more over-rim hand pattern during fast propulsion. Contrary to our first hypothesis, individuals in subset 1 that developed pain after 36 months did not use a more over-rim hand pattern than the no pain group. Similarly, those that had chronic shoulder pain (pain at both 18 and 36 months) did not use more over-rim patterns than individuals whose pain was present at 18 months but had resolved at 36 months, which did not support our second hypothesis. Our third hypothesis was partially supported: weaker shoulder adductors were significantly correlated to higher NRT values in the first subset, but not in the second.

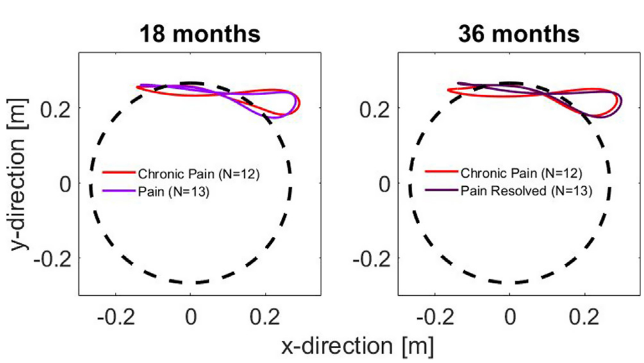

Fig. 3. Hand patterns at 18 and 36 months for individuals with pain at both time points (Chronic Pain, red) and individuals with pain at 18 months whose pain resolved at 36 months (Pain Resolved; purple = pain present, dark purple = pain resolved). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Clinical recommendations for wheelchair propulsion technique suggest MWCU use under-rim patterns (PVACSCM, 2005). Indeed, individuals in the No Pain group did use more DL patterns than any other pattern, which has been recommended for wheelchair propulsion along with SC (e.g.,Kwarciak et al., 2012; Slowik et al., 2016b). However, the lack of statistical significance and high variability in hand pattern across subjects suggests that previously reported differences in propulsion variables (handrim forces and spatiotemporal measures) between hand patterns may not yield significantly different pain outcomes. Even though individuals who developed pain tended toward SL patterns (e.g., had higher NRT values) that require higher muscle power and stress, cadence and handrim forces (Kwarciak et al., 2012; Slowik et al., 2016b), the difference in NRT between the pain and no pain groups was not significant and the variability in NRT was high (Table 3). Similarly, the hand pattern used during fast propulsion in individuals reporting shoulder pain did not predict future pain resolution. Thus, differences in handrim forces or cadence as a result of using a different hand pattern may not be large enough to avoid developing shoulder pain or to mitigate present shoulder pain. In fact, some studies have not found kinetic measures (Boninger et al., 2002; Raina et al., 2012; Richter et al., 2007) or rotator cuff compression risk (Madansingh et al., 2020) to be significantly different between hand patterns, suggesting that simply changing hand patterns is not a sufficient approach to preventing or mitigating shoulder pain. Therefore, shoulder pain development may be more related to an individual's strength rather than specific biomechanical variables during propulsion such as hand pattern.

Although lower levels of shoulder strength have been correlated with shoulder pain in this group of MWCU (Mulroy et al., 2015), there has not been conclusive evidence for the relationship between shoulder strength and the hand pattern used during fast propulsion. One study showed that with strength training, an increase in power output was accompanied by a decrease in cadence in MWCU (Rodgers et al., 2001) but they did not analyze whether the hand pattern changed with strength training. Other studies, however, found that increased shoulder strength was correlated to higher handrim forces, but not to cadence (Ambrosio et al., 2005). This would suggest that the correlation between shoulder strength and hand pattern found in the first subset is not necessarily associated with higher cadence or handrim forces typically seen when using the SL pattern (Kwarciak et al., 2012). On the other hand, subset 2 did not show a significant correlation between NRT and adduction strength. However, model fit values were similar between the subsets (subset 1 marginal R^2 = 0.019, subset 2 marginal R^2 = 0.035), indicating that the difference in statistical significance may have been due to the difference in sample sizes. Regardless of significance, the marginal R^2 values in both models were low, indicating large variability in this correlation. Thus, over-rim patterns may be loosely correlated to shoulder adductor muscle weakness, but future work is needed to verify the clinical significance of this relationship.

A potential limitation of this study was that we analyzed propulsion only at participants' fastest comfortable speed. Wheelchair propulsion at faster speeds leads to more over-rim propulsion patterns (Boninger et al., 2002; Slowik et al., 2015). The average speed of the no pain group in subset 1 was higher than the pain group (Table 1), which should lead to higher NRT values. However, the no pain group had lower NRT values than the pain group. Thus, the SL pattern used by the pain group was not a result of their faster propulsion. An additional limitation is that the generalizability of these findings may be limited. Only four of the 60 participants in subset 1 and three of the 25 participants in subset 2 were female, and all had a complete spinal cord injury. Thus, it is unknown if these results are generalizable to female MWCU as well as other populations of MWCU outside of paraplegia caused by a spinal cord injury. A final limitation is that pain was represented as a binary outcome. Individuals with pain were not separated by degree or location of pain, and thus the variability and subjectivity among individuals makes it difficult to identify relationships between propulsion mechanics and shoulder pain. Categorizing individuals into groups based on whether pain was or was not present was sufficient for this study in order to identify correlations related to any level of shoulder pain. However, future work should analyze how shoulder strength and hand pattern vary with different levels and locations of shoulder pain.

In summary, this study showed that the hand pattern used during fast wheelchair propulsion is not correlated with shoulder pain development or mitigation. In addition, shoulder adductor weakness, a predictor of shoulder pain, was correlated with more over-rim hand patterns in the first subset of subjects, but not in the second. Therefore, more work is needed to determine the robustness of the relationship between hand pattern and shoulder strength before using the SL pattern as an indicator of weaker shoulder adductors. Future work should analyze how propulsion mechanics change with shoulder strength as well as the factors contributing to decreased shoulder pain over time in order to improve the rehabilitation outcomes for MWCU.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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