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Biological Sex-Related Differences in Glenohumeral Dynamics Variability during Pediatric Manual Wheelchair Propulsion*

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Abstract— **Shoulder pain and pathology are extremely common in adult manual wheelchair users with spinal cord injury (SCI). Within this population, biological sex and variability in shoulder joint dynamics have been shown to be important contributors to both shoulder pain and pathology. Sex-related differences in shoulder dynamics variability during pediatric manual wheelchair propulsion may influence a user's lifetime risk of shoulder pain and pathology. The purpose of this study was to assess the influence of biological sex on variability in three-dimensional (3-D) glenohumeral joint dynamics in pediatric manual wheelchair users with SCI. An inverse dynamics model computed 3-D glenohumeral joint angles, forces, and moments of 20 pediatric manual wheelchair users. Levene's tests assessed biological sex-related differences in variability. Females exhibited less variability in glenohumeral joint kinematics and forces, but greater variability in joint moments than males. Evaluation of glenohumeral joint dynamics with consideration for biological sex and variability strengthens our interpretation of the relationships among shoulder function, pain, and pathology in pediatric manual wheelchair users.**

Clinical Relevance— **Female pediatric manual wheelchair users may be at an increased risk of shoulder repetitive strain injuries due to decreased glenohumeral joint motion and force variability during propulsion. This work establishes quantitative methods for determining the effects of biological sex on the variability of shoulder joint dynamics.**

I. Introduction

The manual wheelchair is the most widely used assistive mobility device for children living with spinal cord injuries (SCI) worldwide [1, 2]. Due to the repetitive shoulder loading inherent to manual wheelchair use, approximately 84% of adult users suffer from shoulder pain and up to 100% present with shoulder pathologies [3, 4]. The prevalence of shoulder pain, however, is far lower in pediatric manual wheelchair users, as well as adult manual wheelchair users with pediatric-onset SCI [3, 5]. Quantitative research investigating shoulder biomechanics in pediatric manual wheelchair users is warranted to enhance our understanding of how to develop interventions for treating shoulder pain and pathology across the lifespan.

Biological sex-related differences in shoulder biomechanics may partially explain why shoulder pain and pathologies are more prevalent among adult female manual wheelchair users [6]. Adult females utilize greater peak glenohumeral joint internal-external rotation angles and range of motion, and greater hand-rim forces than adult males [6-9]. However, findings in adults may not reflect what occurs in children, as biological sex-related differences during musculoskeletal development may result in differences in skeletal growth and muscle mass distribution [10]. In addition, data obtained from adults cannot simply be scaled down to children. Our group found that the biological sex-related differences in shoulder biomechanics previously observed in adults do not apply to pediatric manual wheelchair users [11]. Thus, it is necessary to consider the influence of biological sex on shoulder joint dynamics in pediatric manual wheelchair users.

Decreased joint dynamics variability during manual wheelchair propulsion is associated with increased shoulder pain and pathology [12-15]. Decreased variability in glenohumeral forces and/or moments may lead to overload of soft tissue structures, which can result in repetitive strain injuries and pain. Inter-cycle variability in spatiotemporal parameters [14], hand-rim forces [13], shoulder kinetics [14], and scapular motion [12] is lower in adult manual wheelchair users with shoulder pain than those without. A connection between biomechanical variability and biological sex also exists. Adult females exhibit reduced kinematic variability compared to males during lower extremity activities, like running [16] and reduced neuromuscular variability during repetitive pointing, elbow flexion, and screwing tasks [17]. However, it remains unknown if biological sex-related differences in variability exist during pediatric manual wheelchair propulsion. This information has the potential to inform the development of therapies to prevent or reduce shoulder pain and pathology, such as impingement and tendinopathy. Therefore, the purpose of this study was to assess the influence of biological sex on variability of 3-D glenohumeral joint dynamics during propulsion in pediatric manual wheelchair users with SCI. We hypothesized that variability in glenohumeral joint dynamics (peak angles,

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forces, and moments) would be lower in female pediatric manual wheelchair users than in males.

II. Methods

A. Experimental Protocol

The Western Review Board approved all study procedures and written informed consent or assent were obtained prior to the collection of any data. Participants self-reported pain on a visual analog scale (VAS) where 0 indicated 'no pain' and 100 indicated 'severe pain' [18]. Anthropometric measurements were obtained, and passive retroreflective markers were placed on 27 anatomical landmarks on the torso and upper extremities [19]. To obtain 3-D hand-rim forces and moments, an instrumented SmartWheel (Out-Front, Pasco, WA) replaced the dominant side wheel of the participant's personal wheelchair. Participants propelled their wheelchairs along a straight 15-meter tiled path using a self-selected speed and propulsion pattern. Each participant performed 5-10 propulsion trials while a 14-camera Vicon (Vicon Motion Systems, Oxford, United Kingdom) motion capture system obtained 3-D trajectories of each marker at 120 Hz, and simultaneously acquired hand-rim kinetics at 240 Hz. Wheelchair fit parameters were not controlled for.

TABLE I. Mean ± SD Participant Demographics and Anthropometrics

	Females (n=9)	***Males (n=11)***	***p***	t_{18}
Age (yrs)	13.3±4.9	14.7±4.2	0.48	0.71
Height (cm)	145±24	160±25	0.20	1.33
Weight (kg)	38.9±12.6	52±17.4	0.07	1.92
Time since (yrs)	4.8±4.1	5.4±4.6	0.79	0.27
Hum. Lgth. (cm)	26.4±3.9	28±3.3	0.14	1.54
Hum. Circ. (cm)	25.3±3.4	27.0±4.3	0.35	0.96
Fore. Lgth. (cm)	21.9±3.3	24.2±2.9	0.12	1.63
Fore. Circ. (cm)	22.3±2.6	24.0±3.6	0.23	1.24
Hand Lgth. (cm)	16.2±2.2	17.4±1.4	0.15	1.50
Hand Circ. (cm)	17.9±1.6	18.6±1.8	0.35	0.96
VAS Pain (0-100)	1.7±5.0	1.8±4.0	0.94	0.08

B. Data Analysis

Marker trajectories were processed in Vicon Nexus software and filtered with a Woltring quintic spline filter (MSE = 20 mm^2) [20]. Hand-rim kinetics were low-pass filtered using a 32-tap finite impulse response filter. Using MATLAB (MathWorks, Inc, Natick MA, USA), hand-rim kinetics data were resampled at 120 Hz. Stroke cycles were divided into contact and recovery phases based on the resultant force applied to the hand-rim [21]. Data were analyzed for each stroke cycle. Starting and stopping stroke cycles were excluded to eliminate acceleration effects. Maximum and minimum peak glenohumeral joint angles, forces, and moments of the participant's dominant arm were identified. The difference between maximum and minimum angles represented the joint range of motion. Forces were normalized to the participant's body weight (%BW), and moments were normalized to the product of each participant's body weight and height (%BWxheight).

C. Upper Extremity Biomechanical Model

An upper extremity inverse dynamics model computed 3-D glenohumeral joint angles, forces, and moments [19]. Segment coordinate systems followed the International Society of Biomechanics (ISB) convention with the Z-axis (flexion/extension) pointing laterally toward the participant's right side, the X-axis (abduction/adduction) pointing anteriorly, and the Y-axis (internal/external rotation) pointing superiorly [22]. A Z-X-Y Cardan rotation sequence calculated 3-D glenohumeral joint angles of the humerus relative to the scapula. Body segment parameters, including mass, center of mass, and inertias, were calculated using regression equations developed specifically for the pediatric population [23].

D. Statistical Analysis

All statistical analyses were performed in MATLAB. Group differences in demographics and anthropometrics were assessed using independent samples t-tests. Group differences in glenohumeral joint dynamics magnitudes were computed with a separate linear mixed-effects model for each of the 21 variables. These models included group as a fixed factor, random intercepts for randomness at the subject level, and a Bonferroni-adjusted critical alpha of 0.002. We tested our hypothesis that female pediatric manual wheelchair users would exhibit less variability in glenohumeral joint dynamics than males using Levene's tests for homogeneity of variances.

III. Results

A. Glenohumeral Kinematics

No biological sex-related differences in glenohumeral ranges of motion or peak joint angle magnitudes in any of the three planes of motion were observed (R^2 *range:* 0.67-0.98, *all* $F_{1,355} \leq 6.31$, $p \geq 0.012$). However, male participants exhibited greater variability in coronal (adduction/abduction) ($F_{1,355}=40.1$, $p<0.001$) and sagittal (flexion/extension) ($F_{1,355}=18.1$, $p<0.001$) plane glenohumeral joint ranges of motion (Fig. 1). Similarly, male participants also exhibited significantly greater variability in maximum glenohumeral adduction ($F_{1,355}=14.0$, $p<0.001$) and external rotation angle ($F_{1,355}=10.8$, $p=0.001$).

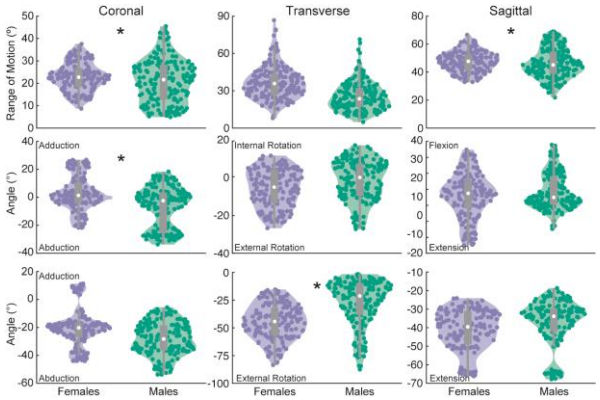

Figure 1. Group differences in variance of glenohumeral range of motion (top) and maximum angle in the positive (middle) and negative (bottom) directions in each plane of motion. Boxplots representing medians and interquartile ranges are visualized in gray. Individual participant data for each stroke cycle are presented as closed purple or green dots. Significant group differences ($p<0.002$) are indicated by asterisks (*).

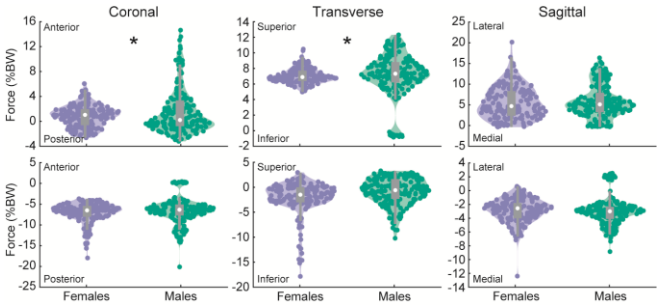

Figure 2. Group differences in the variance of maximum glenohumeral joint force in the positive (top) and negative (bottom) directions along each axis. Boxplots representing medians and interquartile ranges are visualized in gray. Individual participant data for each stroke cycle are presented as closed purple or green dots. Significant group differences (p<0.002) are indicated by asterisks (*).

B. Glenohumeral Kinetics

No biological sex-related differences in glenohumeral joint force or moment magnitudes were observed (R^2 *range:* 0.34-0.84, *all* $F_{1,355}$≤2.19, p≥0.14). However, male participants exhibited greater variability in maximum anterior ($F_{1,355}$=24.6, p<0.001) and superior force ($F_{1,355}$=57.6, p<0.001) when compared to females (Fig. 2). Conversely, female participants exhibited greater variability in maximum glenohumeral flexion ($F_{1,355}$=50.6, p<0.001) and abduction moment ($F_{1,355}$=21.4, p<0.001) (Fig. 3).

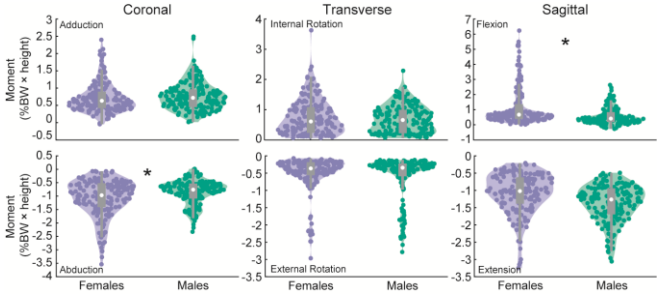

Figure 3. Group differences in the variance of maximum glenohumeral joint moment in the positive (top) and negative (bottom) directions about each plane of motion. Boxplots representing medians and interquartile ranges are visualized in gray. Individual participant data for each stroke cycle are presented as closed purple or green dots. Significant group differences (p<0.002) in variability are indicated by asterisks (*).

IV. Discussion

The current study is the first to comprehensively assess biological sex-related differences in glenohumeral joint kinematic variability in any manual wheelchair user population. Our results indicate that males utilize greater variability in glenohumeral joint motion than female participants. Our findings echo those from studies of biological sex-related movement variability during repetitive, lower extremity tasks. During running, adult females exhibit lower variability in joint kinematics than males [16, 24, 25]. The sex-related differences in glenohumeral joint motion variability observed in the current study could be explained by the unique motion control strategies executed by males and females [17]. Specifically, it has been demonstrated that adult females often employ upper extremity movement strategies that sacrifice variability for precision [26, 27]. Findings from previous research are limited in that they do not include pediatric participants. Because adults with lower movement variability are at an increased risk of musculoskeletal injury due to overuse [28], it is critical that future research determines how manual wheelchair movement variability in childhood influences shoulder injury risk over the lifespan.

The current study represents a significant advancement over previous work regarding kinetics, which was limited to assessing variability in thoracohumeral kinetics or hand rim forces during manual wheelchair propulsion in adults. We found that male pediatric manual wheelchair users exhibited greater variability in peak glenohumeral joint anterior and superior forces than females. This observation aligns with previous work that suggests males and females utilize sex-specific force control strategies. Specifically, Svendsen and Madeleine found that during an unconstrained, repetitive elbow flexion force task, adult females exhibit lower variability in both task-specific force (the force aligned with the primary direction of the task) and tangential forces when compared to males [29]. Sex-related differences in force variability may reflect sex-specific neuromuscular control strategies. During a repetitive screwing task, adult females exhibited significantly lower variability in biceps brachii and flexor carpi radialis muscle activity than males [17]. Similarly, in a repetitive pointing task, variability in biceps brachii activity was lower in females than males [30]. Reduced shoulder force variability during manual wheelchair propulsion may lead to the risk of soft tissue repetitive strain injuries [28]. Able-bodied adults that perform daily upper extremity tasks are about 2.3x more likely to experience a repetitive strain injury of the shoulder if the task requires high repetition and high force [28]. Our results indicate that female pediatric manual wheelchair users may be at an increased risk of such repetitive strain injuries due to lower variability of force applied throughout a lifetime of wheelchair use.

Despite exhibiting lower variability in glenohumeral joint motion and force than males, females exhibited greater variability in peak glenohumeral joint abduction moments and flexion moments. These findings may possess significant clinical relevance, however more work is needed to determine the impact. A longitudinal assessment of adult manual wheelchair users found that patients that developed shoulder pain exhibited higher variability in shoulder abduction moments at baseline [15]. Additionally, it was found that the statistical interaction term consisting of glenohumeral joint flexion-extension and adduction moments was a significant predictor of shoulder pain [15]. These findings are of importance to the current study, as female pediatric manual wheelchair users exhibited greater variability in both flexion and adduction moments. However, it is unclear what is driving the sex-related differences in glenohumeral joint moments observed in the current study. While men are generally larger and possess longer upper extremity segments, our groups were similar regarding segment lengths, height, and weight [31]. Perhaps accounting for the weight of the wheelchair when normalizing kinetics would improve our understanding and shoulder be considered in future work. Future research may also include a more comprehensive characterization of anthropometrics and musculoskeletal morphology and their

influence on shoulder biomechanical variability, as boys and girls develop at very different rates and timescales. Combined with results from previous work in adult manual wheelchair users [15], our findings suggest that female pediatric manual wheelchair users are potentially at an increased risk of shoulder pain or pathology due to greater variability in glenohumeral joint abduction and flexion moments.

V. Conclusion

Biological sex-related differences in the variability of glenohumeral joint kinematics and kinetics exist in pediatric manual wheelchair users with SCI, even in the absence of differences in means. Quantifying glenohumeral joint dynamics with consideration for biological sex and variability strengthens the interpretation of the relationship among shoulder joint function, shoulder pain and shoulder pathology in pediatric manual wheelchair users with SCI. Accordingly, it is recommended that future research and clinical decision-making consider an individual's biological sex and account for movement variability when possible.

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