Archives of Rehabilitation Research and Clinical Translation (2022) 4, 100235

ACRM
AMERICAN CONGRESS OF REHABILITATION MEDICINE

Archives of Rehabilitation Research and Clinical Translation

Archives of Rehabilitation Research and Clinical Translation 2022;4:100235

Available online at www.sciencedirect.com

Original Research

The Influence of Age at Pediatric-Onset Spinal Cord Injury and Years of Wheelchair Use on Shoulder Complex Joint Dynamics During Manual Wheelchair Propulsion

Joshua M. Leonardis, PhD [a], Alyssa J. Schnorenberg, MS [a], Lawrence C. Vogel, MD [b], Gerald F. Harris, PhD [c,d], Brooke A. Slavens, PhD [a,c]

[a] *Department of Rehabilitation Sciences and Technology, University of Wisconsin-Milwaukee, Milwaukee, WI*
[b] *Shriners Hospitals for Children, Chicago, IL*
[c] *Orthopaedic and Rehabilitation Engineering Center, Marquette University, Milwaukee, WI*
[d] *Department of Biomedical Engineering, Marquette University, Milwaukee, WI*

KEYWORDS
Aging;
Pediatrics;
Rehabilitation;
Scapula

Abstract *Objective:* To assess the association of age at pediatric-onset spinal cord injury (SCI) and years of manual wheelchair use with shoulder dynamics.
Design: Upper extremity kinematics and hand-rim kinetics were obtained during manual wheelchair propulsion. An inverse dynamics model computed three-dimensional acromioclavicular, sternoclavicular, and glenohumeral joint dynamics. Linear mixed effects models evaluated the association of age at injury onset and years of wheelchair use with shoulder dynamics.
Setting: Motion laboratory within a children's hospital.
Participants: Seventeen manual wheelchair users (N=17; 6 female, 11 male; mean age: 17.2 years, mean age at SCI onset: 11.5 years) with pediatric-onset SCI (levels: C4-T11) and International Standards for Neurological Classification of SCI grades: A (11), B (3), C (2), and N/A (2).
Interventions: Not applicable.
Main Outcome Measures: Acromioclavicular, sternoclavicular, and glenohumeral angles and ranges of motion, and glenohumeral forces and moments.

List of abbreviations: CI, confidence interval; $_{C}R^2$, conditional R-squared; $_{M}R^2$, marginal R-squared; MWU, manual wheelchair user; SCI, spinal cord injury

Supported by the National Institute on Disability, Independent Living, and Rehabilitation Research (90RE5006-01-00) and the Eunice Kennedy Shriver Nation Institute of Child Health and Human Development (NICHD) of the NIH (K12HD073945 and 1R01HD098698).
Disclosures: none.
Cite this article as: Arch Rehabil Res Clin Transl. 2022;4:100235

https://doi.org/10.1016/j.arrct.2022.100235

Results: We observed a decrease in maximum acromioclavicular upward rotation (β [95% confidence interval {CI}]=3.02 [0.15,5.89], *P*=.039) and an increase in acromioclavicular downward/upward rotation range of motion (β [95% CI]=0.44 [0.08,0.80], *P*=.016) with increasing age at SCI onset. We found interactions between age at onset and years of use for maximum glenohumeral abduction (β [95% CI]=0.16 [0.03,0.29], *P*=.017), acromioclavicular downward/upward rotation range of motion (β [95% CI]=-0.05 [-0.09,-0.01], *P*=.008), minimum acromioclavicular upward rotation (β [95% CI]=-0.34 [-0.64,-0.04], *P*=.026). A decrease in glenohumeral internal rotation moment (β [95% CI]=-0.09 [-0.17,-0.009], *P*=.029) with increasing years of use was found.
Conclusions: Age at injury and the years of wheelchair use are associated with shoulder complex biomechanics during wheelchair propulsion. These results are noteworthy, as both age at SCI onset and years of wheelchair use are considered important factors in the incidence of shoulder pain. These results suggest that investigations of biomechanical changes over the lifespan are critical.

The manual wheelchair is among the most widely used assistive mobility devices worldwide.[1,2] Shoulder pain and pathology are ubiquitous consequences of use. Approximately three-quarters of manual wheelchair users (MWUs) with spinal cord injury (SCI) experience shoulder pain,[3] and up to 100% will experience shoulder pathologies such as rotator cuff tendinopathy.[4] Shoulder pain or pathology can have a profound effect on MWU quality of life and long-term health.[5-7] Additionally, limited physical activity due to pain or pathology can lead to secondary medical conditions such as obesity or cardiovascular disease.[8] Users with pediatric-onset SCI may live with these secondary medical conditions longer than those with adult-onset SCI. To better serve both populations, it is important to identify factors contributing to shoulder pain and pathology in MWU with pediatric-onset SCI.

The incidence of shoulder pain increases significantly as MWU with pediatric-onset SCI advance from childhood, where shoulder pain affects 7%-26% of users,[9,10] to adulthood when 49%-53% of users experience shoulder pain.[6,9] What occurs during the transition to adulthood to precipitate shoulder pain is unknown. It is reasonable to associate pain as a natural byproduct of the repetitive nature of manual wheelchair use.[11] The average user performs 3500 strokes daily,[12] which frequently results in overuse and repetitive strain injuries of the shoulder. However, wheelchair athletes perform a greater volume of upper extremity activities in addition to the normal demand of manual wheelchair use without any increase in the likelihood of shoulder pain or pathology when compared with non-athletes.[13-15] Moreover, adult MWU with pediatric-onset SCI suffer from shoulder pain less frequently than those with adult-onset SCI, despite greater duration of wheelchair use.[3,6,16] While the etiology of shoulder pain experienced during the transition to adulthood remains unknown, factors other than overuse use must be considered.

Shoulder complex joint dynamics during manual wheelchair propulsion can provide valuable insight into the origins of shoulder pain.[17] Subacromial impingement, a principal factor in rotator cuff pathologies, occurs when the subacromial space is reduced to less than the thickness of the rotator cuff tendons.[18] Several scapular (increasing protraction/decreasing retraction, and anterior tilt/decreasing posterior tilt) and humeral motions (increasing internal rotation/decreasing external rotation) have been implicated in subacromial impingement in healthy adults. In MWUs, increasing glenohumeral superior force during propulsion is linked to increasing prevalence of shoulder pathology.[17] Large superior forces may precipitate pathology by superiorly translating the humeral head within the glenoid, reducing the subacromial space.[19-21] Moreover, a longitudinal evaluation of MWU found that the development of shoulder pain was associated with decreasing glenohumeral flexion/extension range of motion and elevation and scapular downward rotation.[22] However, it is unknown if or how shoulder dynamics change as MWU with pediatric-onset SCI age. An evaluation of the effects of age at SCI onset and years of wheelchair use on shoulder complex joint dynamics could provide powerful insight into the mechanisms underlying shoulder pain in MWU with pediatric-onset SCI.

Therefore, the purpose of this study was to assess the association of age at pediatric-onset SCI and years of manual wheelchair use with shoulder complex motions, forces, and moments. The risk of shoulder pain increases with increasing years of wheelchair use and increasing age at SCI onset and is linked with decreasing scapular downward rotation, increasing scapular internal rotation and anterior tilt, decreasing glenohumeral elevation, and increasing glenohumeral superior force. As such, we tested the primary hypothesis that users would propel their wheelchairs with increasing scapular downward rotation, decreasing scapular internal rotation and anterior tilt, decreasing glenohumeral elevation, and increasing glenohumeral superior force with increasing age at SCI onset and years of wheelchair use.

Methods

Participants

An a priori sample via size via power analysis was not conducted because of the exploratory nature of the study. Our convenience sample of 17 participants represented the number of individuals that could be feasibly recruited from our region. Seventeen MWU with pediatric-onset SCI were

Table 1 Mean (95% CI) participant demographics, injury characteristics, and anthropometrics

N	17
Sex (F/M)	6/11
Age (y)	17.2 (14.7, 19.8)
Age range (y)	10.2-29.6
Height (cm)	163.9 (151.6, 179.3)
Weight (kg)	54.0 (44.9, 63.1)
Post-injury (y)	5.8 (3.3, 8.2)
Age at onset (y)	11.5 (7.9, 15.0)
SCI Level	C4-T11
ISNCSCI grade	A (11), B (3), C (2), N/A (2)
Handedness (L/R)	4/13
Hum. length (cm)	29.9 (28.2, 31.7)
Hum. circ. (cm)	27.9 (26.0, 29.8)
Fore. length (cm)	24.6 (23.1, 26.0)
Fore. circ. (cm)	24.9 (22.9, 26.8)
Hand length (cm)	17.4 (16.4, 18.4)
Hand circ. (cm)	19.1 (18.2, 20.0)
VAS pain (0-100)	0.47 (0, 0.96)

NOTE. Two participants had never been provided an ISNCSCI grade.
Abbreviations: F, female; Fore. circ., circumference at midpoint of forearm; Fore. length, length of forearm; Hand circ., circumference of hand at knuckles; Hum. circ., circumference at midpoint of upper arm; Hum. length, length of upper arm; ISNCSCI grade, International Standards for Neurological Classification of SCI Grades; L, left; M, male; R, right; VAS, visual analog scale.

included in this cross-sectional study (table 1). Participants were between the ages of 10 and 30, which was chosen to capture the peak of musculoskeletal developmental activity (ages 10-21), the end of musculoskeletal development (age ~24), and several years of adulthood (ages 27-30).[23-26] Participants were medically diagnosed with an SCI more than 1 year prior to enrollment and utilized a manual wheelchair as their primary mode of mobility. Exclusion criteria included the presence or history of any neuromuscular or orthopedic conditions of the upper extremity, or treatment to the upper extremities within the previous 12 months with botulinum toxin A. The Western Institutional Review Board approved all included procedures. Written informed assent or consent was obtained prior to onset of experimental procedures.

Experimental procedures

All procedures were completed in a single experimental session. At the onset of this session, participants self-reported their current, general pain level using the visual analog scale, where 100 indicated severe pain and 0 indicated no pain[27] (table 1). Following the reporting of pain, height, weight, and hand, forearm, and humerus lengths and circumferences were obtained (table 1). Participants were then outfitted for motion analysis with 27 passive, retroreflective markers on anatomic landmarks located on the torso and bilateral upper extremities.[28] The dominant side wheel of their personal wheelchair was replaced with an instrumented so that three-dimensional hand-rim forces and moments could be obtained (240 Hz) synchronously with the three-dimensional marker trajectories collected by a multicamera Vicon motion capture (120 Hz). Participants propelled their wheelchairs along a 15-meter tiled path at a self-selected speed and propulsion pattern. Each participant performed 5-10 trials which consisted of multiple propulsion cycles. Participants performed a range of propulsion trials to ensure 10 strokes of acceptable quality were acquired. The exact number of trials varied because of individual differences depending on stroke cycle time and propulsion distance within the capture volume.

Data analysis and modeling

Motion capture marker trajectories were filtered with a Woltring quintic spline filter in MATLAB[c] (mean squared error=20 mm^2) while hand-rim kinetics were low-pass filtered using a 32-tap finite impulse response filter[a].[29] Hand-rim kinetics were resampled at 120 Hz to match the sampling frequency of motion capture marker trajectories[c]. Data were analyzed at the stroke level, with stroke cycles divided into contact and recovery phases based on the force applied to the hand rim.[30] The initial (starting) and final (stopping) stroke cycles from each trial were discarded to avoid adverse effects of acceleration on the interpretation of our findings. Although strokes with high acceleration may be of interest in future work because of the demand they place on the upper extremity, the purpose of the current study was to characterize biomechanics utilized during steady state propulsion.

Three-dimensional shoulder complex joint biomechanics were computed with a bilateral upper extremity inverse dynamics model developed for MWU.[28] Of interest to the current study were dominant side kinematics, including 3 degrees-of-freedom acromioclavicular and glenohumeral joint motion and 2 degrees-of-freedom sternoclavicular joint motion. Segment coordinate systems adhered to International Society of Biomechanics standards.[31] A Z-X-Y Cardan rotation sequence calculated glenohumeral joint angles of the humerus relative to the scapula, while a Y-X-Z rotation sequence calculated sternoclavicular angles of the clavicle relative to the sternum and acromioclavicular joint angles of the scapula relative to the clavicle. Segment parameters such as masses, centers of mass, and inertias were computed from valid regression equations.[32]

Maximum and minimum sternoclavicular, acromioclavicular, and glenohumeral joint angles, and maximum and minimum glenohumeral joint forces and moments were quantified in each plane of motion for participants' dominant side. The difference between the maximum and minimum joint angles represented a joint's range of motion. To increase the interpretability of data obtained from participants that varied in size, joint forces were normalized to each participant's body weight and moments were normalized to the product of bodyweight and height.

Statistical analysis

Statistical analyses were performed in MATLAB[c]. Data from every stroke performed by each participant were analyzed using linear mixed effects models to account for correlation between data within each subject[c]. We tested the primary hypothesis that users would propel their wheelchairs with increasing scapular downward rotation, decreasing scapular internal rotation and anterior tilt, decreasing glenohumeral elevation, and increasing glenohumeral superior force with increasing age at SCI onset and years of wheelchair use using separate linear mixed effects models for each variable. On an exploratory basis, we evaluated all remaining shoulder complex joint dynamics metrics (remaining glenohumeral dynamics, acromioclavicular and sternoclavicular kinematics) using separate linear mixed effects models for each variable. These models included age at SCI onset and years of manual wheelchair use as fixed factors, while random intercepts controlled for subject level variation. The interaction between age at SCI onset and years of wheelchair use was also evaluated. These analyses utilized a significance level of P<.05. Marginal ($_{M}R^2$) and conditional ($_{C}R^2$) R^2 values determined the variance accounted for solely by the fixed effects of age at SCI onset and years of wheelchair use and by the combination of fixed effects and subject variation.[33]

Results

Shoulder complex joint kinematics

The goodness of fit for models describing shoulder complex joint kinematics was moderate to excellent (mean [95% confidence interval {CI}] R^2: 0.82 [0.78, 0.87]). No main effect of years of wheelchair use was observed for maximum or minimum joint angles (fig 1) or ranges of motion (fig 2) (all $F_{1,265}$≤2.11, P≥.14).

There was a main effect of age at SCI onset on maximum acromioclavicular joint angle in the coronal (downward/upward rotation) plane (*β* [95% CI]=3.02 [0.15, 5.89], $F_{1,265}$=4.28, P=.039, $_{M}R^2$=0.22, $_{C}R^2$=0.99) and downward/upward rotation range of motion (*β* [95% CI]=0.44 [0.08, 0.80], $F_{1,265}$=5.90, P=.016, $_{M}R^2$=0.23, $_{C}R^2$=0.72), indicating a decrease in maximum upward rotation (shift toward downward rotation) and an increase in downward/upward rotation range of motion with increasing age at SCI onset (figs 3 and 4).

Finally, interactions between age at SCI onset and years of wheelchair use were observed in maximum glenohumeral abduction (*β* [95% CI]=0.16 [0.03, 0.29], $F_{1,265}$=5.78, P=.017, $_{M}R^2$=0.22, $_{C}R^2$=0.22), minimum acromioclavicular upward rotation (*β* [95% CI]=-0.34 [-0.64, -0.04], $F_{1,265}$=5.05, P=.026, $_{M}R^2$=0.22, $_{C}R^2$=0.99), and total acromioclavicular downward/upward rotation range of motion (*β* [95% CI] =-0.05 [-0.09, -0.01], $F_{1,265}$=7.05, P=.008, $_{M}R^2$=0.23, $_{C}R^2$=0.72) (fig 5). These findings suggest that individuals who experience an SCI early in childhood experience an increase in maximum glenohumeral abduction and acromioclavicular downward/upward rotation range of motion and a decrease in minimum acromioclavicular upward rotation with

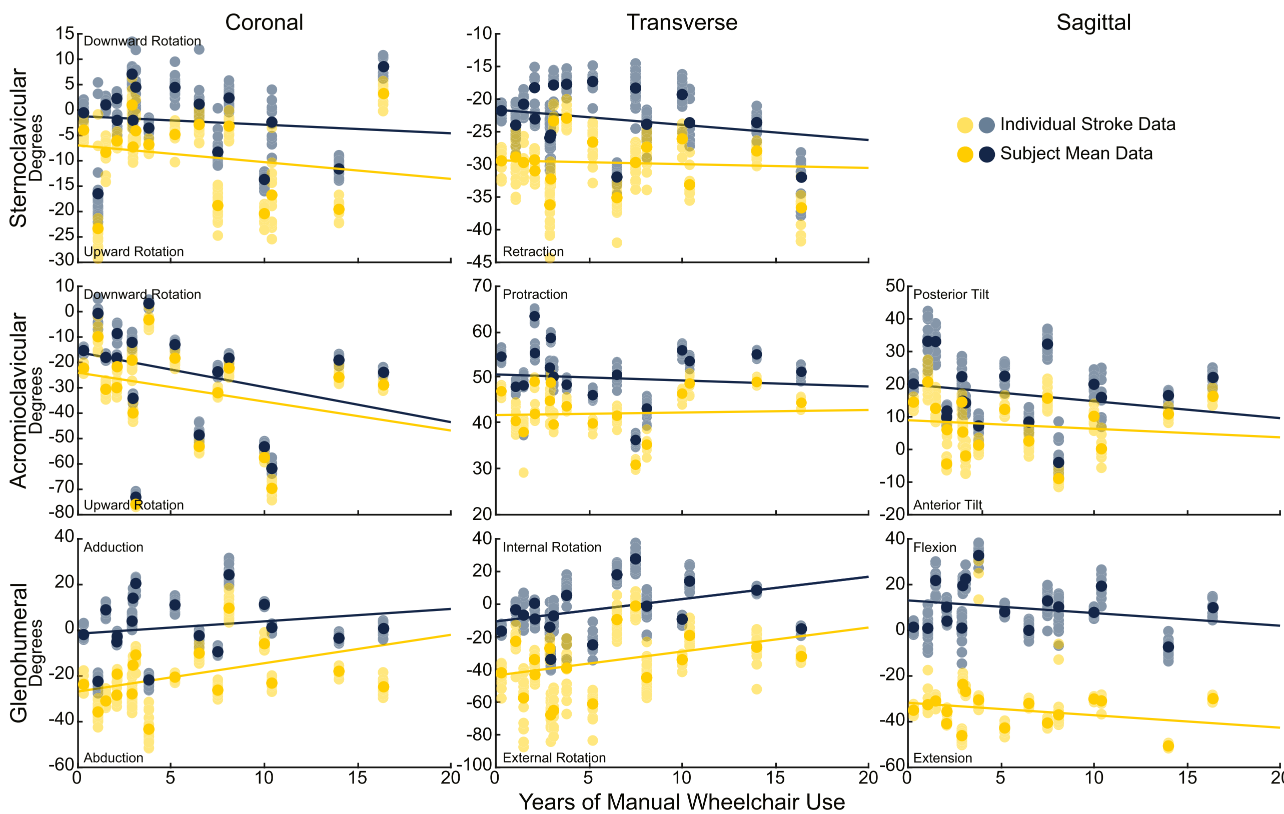

Fig 1 Scatterplots representing the relation between maxima/minima shoulder complex joint angles and years of manual wheelchair use. Maxima/minima joint angles in each direction of each measurement plane are visualized in blue and gold. Participant means are represented as opaque blue or gold markers, while individual stroke data for each participant are represented as transparent blue or gold markers. Least squares lines of best fit illustrate trends in relation to years of wheelchair use.

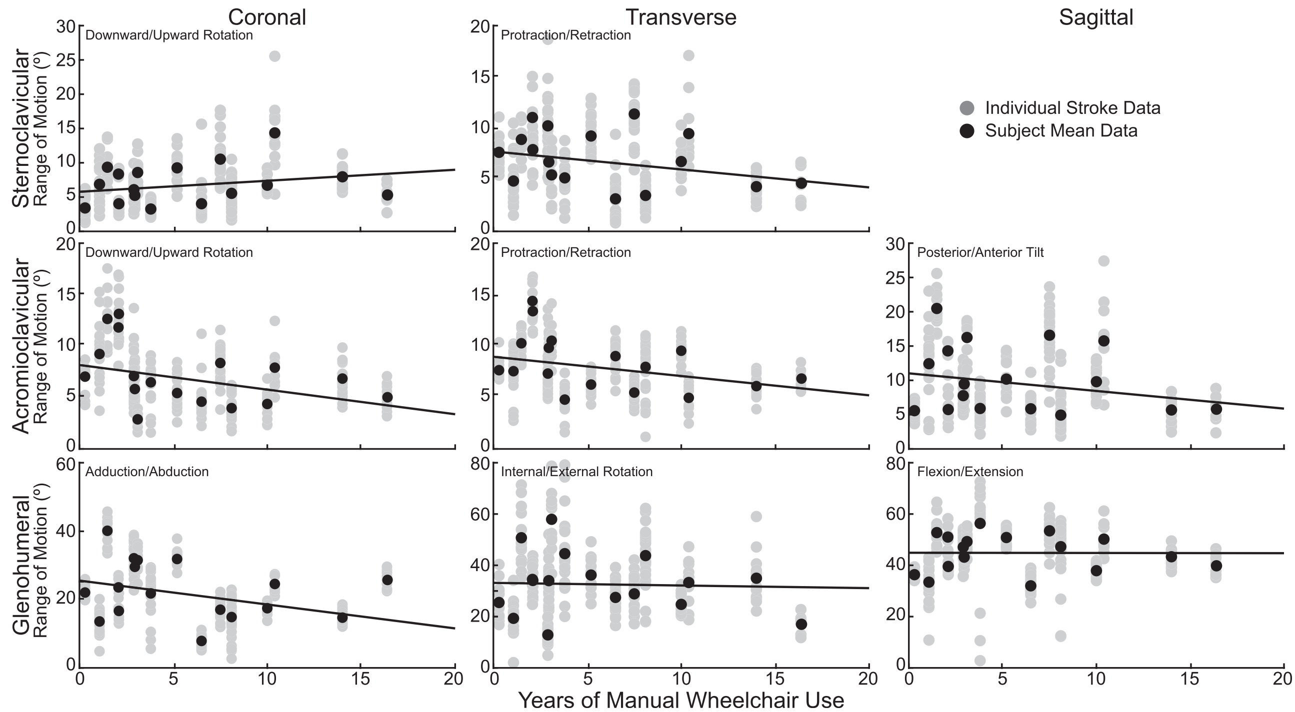

Fig 2 Scatterplots representing the relation between shoulder complex joint range of motion and years of manual wheelchair use. Participant means are represented as opaque black markers, while individual stroke data for each participant are represented as transparent black markers. Least squares lines of best fit illustrate trends in relation to years of wheelchair use.

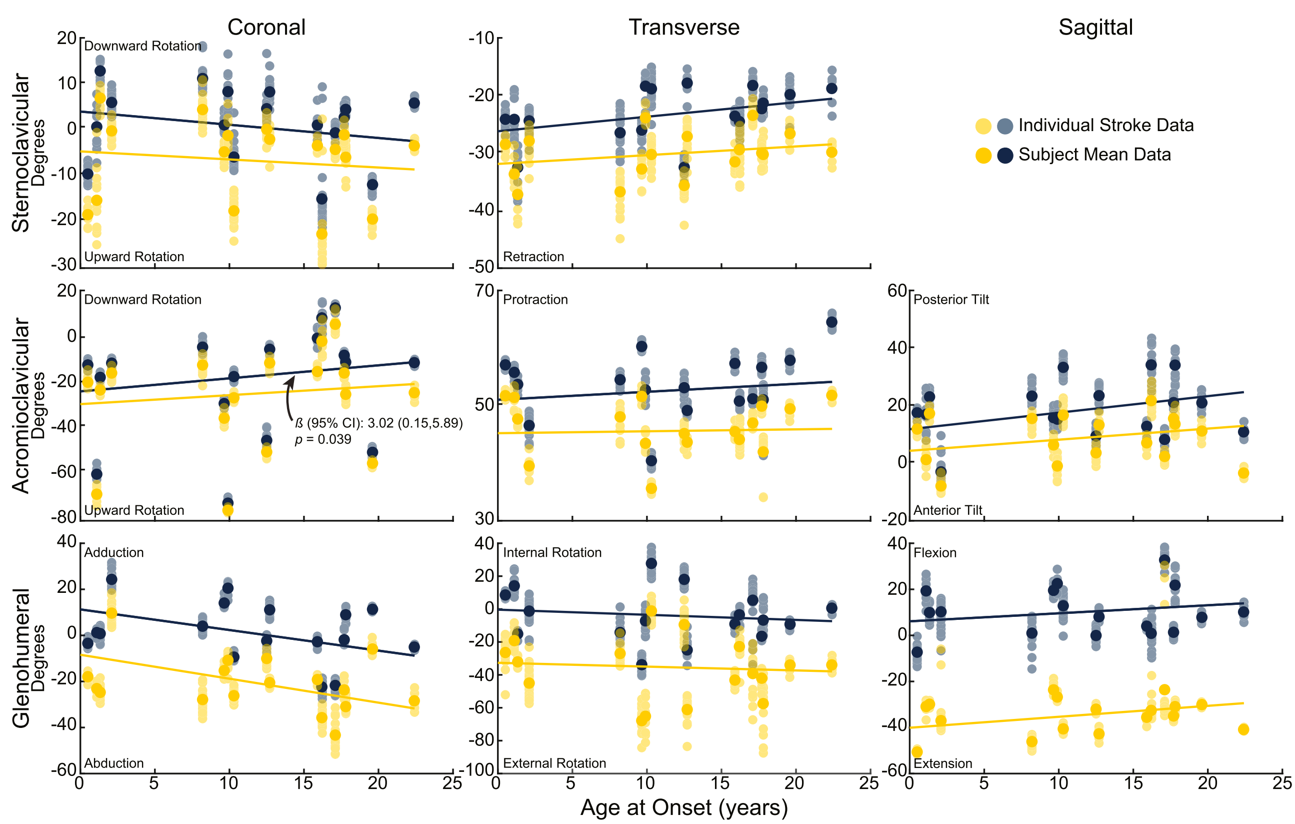

Fig 3 Scatterplots representing the relation between maxima/minima shoulder complex joint angles and age at spinal cord injury onset. Maxima/minima joint angles in each direction of each measurement plane are visualized in blue and gold. Participant means are represented as opaque blue or gold markers, while individual stroke data for each participant are represented as transparent blue or gold markers. Least squares lines of best fit illustrate trends in relation to age at onset. Significant findings are accompanied by model statistics.

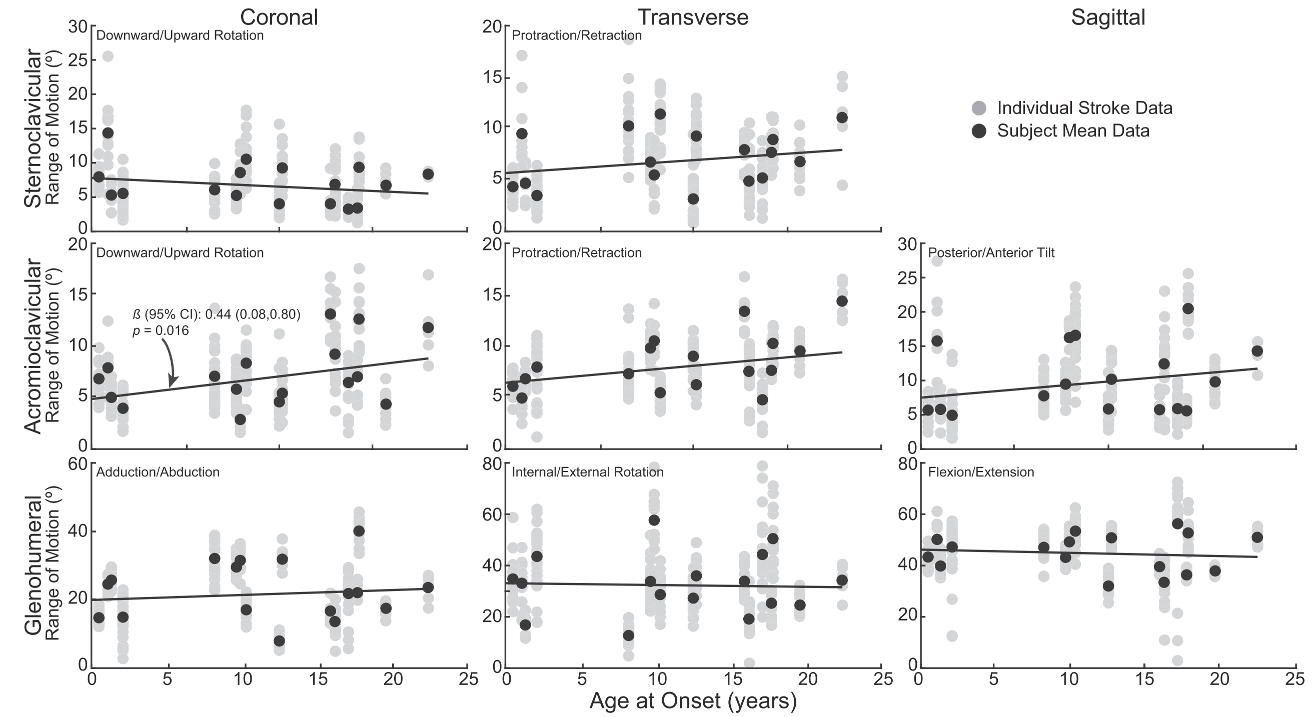

Fig 4 Scatterplots representing the relation between shoulder complex joint range of motion and years of manual wheelchair use. Participant means are represented as opaque black markers, while individual stroke data for each participant are represented as transparent black markers. Least squares lines of best fit illustrate trends in relation to age at onset. Significant findings are accompanied by model statistics.

increasing years of wheelchair. Contrarily, an individual who experiences an SCI in early adulthood would experience the opposite, a decrease in maximum glenohumeral abduction and acromioclavicular coronal plane range of motion and an increase in acromioclavicular upward rotation with increasing years of wheelchair use.

Glenohumeral joint kinetics

Our statistical models of glenohumeral joint forces and moments generally described our experimental data moderately well (mean [95% CI] R^2: 0.48 [0.42, 0.54]). There was a main effect of years of wheelchair use on glenohumeral internal rotation moment (β [95% CI]=-0.09 [-0.17, -0.009], $F_{1,265}$=4.79, P=.029, $_{M}R^2$=0.10, $_{C}R^2$=0.58) (fig 6), indicating a decrease in internal rotation moment with increasing years of manual wheelchair use.

No main effects of age at SCI onset (all $F_{1,265} \leq 3.47$, $P \geq .06$) (fig 7), or interactions between years of wheelchair use and age at SCI onset (all $F_{1,265} \leq 2.83$, $P \geq .09$) were observed for any glenohumeral kinetics.

Discussion

The incidence of shoulder pain increases as pediatric MWU transition to adulthood. Shoulder complex joint dynamics during manual wheelchair propulsion provide valuable insight into the risk of developing shoulder pain or pathologies. As such, we quantified shoulder complex biomechanics during manual wheelchair propulsion in MWU with pediatric-onset SCI across a range of ages representing the transition to adulthood. We hypothesized that MWU would increasingly utilize scapular and humeral kinematics previously associated with subacromial impingement and rotator cuff pathology with increasing age at SCI onset and years of wheelchair use. Our findings partially support this hypothesis. We found that upward rotation of the acromioclavicular joint, and acromioclavicular coronal plane range of motion were influenced by age at SCI onset. Moreover, we found that the younger one was when SCI was experienced, the greater the increase in maximum glenohumeral abduction and decrease in the minimum scapular upward rotation (a shift toward downward rotation) with increasing years of manual wheelchair use. The combination of increasing glenohumeral abduction and shift toward scapular downward rotation is widely regarded as contributive to subacromial impingement and potentially rotator cuff pathology.

We found that shoulder complex motion was largely unaffected by age at SCI onset or years of wheelchair use. The exceptions to this were the observation that upward rotation of the acromioclavicular joint decreased and acromioclavicular coronal plane range of motion increased with increasing age at SCI onset. In the current study, MWU that experienced an SCI early in childhood (prior to age 10) propelled their wheelchair using a mean ± SD of 40.2° (23.2) scapular upward rotation, whereas those who suffered an SCI after 10 used 27.9° (18.1) of upward rotation. Moreover, as the age at SCI onset increased, total downward/upward rotation range of motion significantly increased, albeit just a few degrees. The role of scapular kinematics in

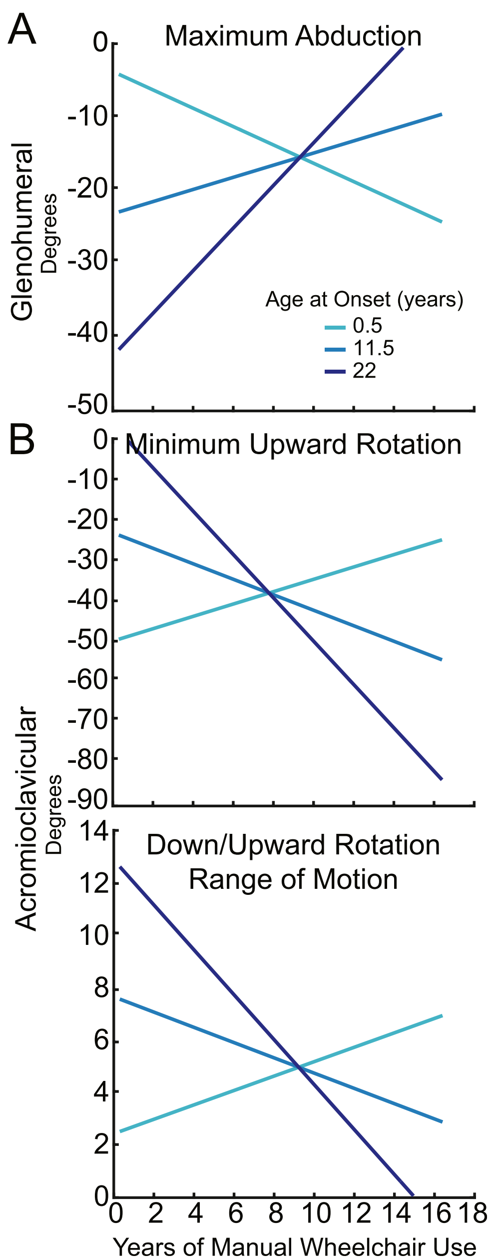

Fig 5 Significant interactions between years of wheelchair use and age at spinal cord injury onset in (A) glenohumeral abduction and (B) acromioclavicular upward rotation and total downward/upward rotation range of motion. Lines represent predictions derived from linear mixed effects model fits describing how the select kinematics would change with years of wheelchair use for a representative subject with the minimum (0.5 years old), median (11.5 years old), and maximum (22.5 years old) age at onset of our experimental population.

subacromial impingement and rotator cuff pathologies is well established in healthy adults. During glenohumeral abduction, individuals with symptoms of subacromial impingement exhibit decreased maximum scapular upward rotation when compared with healthy, age-matched controls.[34-37] Our findings suggest that increasing age at SCI onset may predispose individuals to subacromial impingement or rotator cuff pathology via a shift toward acromioclavicular downward rotation.

Scapular motions previously identified as contributing to subacromial impingement in healthy adults may not reflect problematic kinematics during manual wheelchair propulsion. Specifically, differences in scapular kinematics between healthy adults with and without symptoms of impingement were observed at abduction angles above 70°, whereas our experimental population propelled their wheelchairs using approximately 30° of maximum glenohumeral abduction. Moreover, it has been shown that increasing age is linked to decreasing scapular upward rotation, which suggests that our results may simply be a function of the individual's age.[38] As a secondary analysis, we evaluated the association between participant age and shoulder complex joint dynamics (supplementary tables S1-S3). However, we found no effect of age on any shoulder dynamics in our study population. Our experimental population was between the ages of 10 and 30, which covers the entire transition to adulthood, but only accounts for a portion of the entire lifespan. Future work should expand this secondary analysis to include a wider range of ages. Nevertheless, our findings reinforce the need to establish the relation between shoulder complex joint kinematics during manual wheelchair propulsion in childhood and the development of shoulder pain or pathology later in life.

A novel and innovative aspect of the current study was our consideration of the interaction between age at SCI onset and years of wheelchair use on shoulder complex biomechanics. We found that the younger one experienced an SCI, the greater the increase in glenohumeral abduction and acromioclavicular downward/upward rotation range of motion and decrease in acromioclavicular upward rotation with increasing years of manual wheelchair use. As previously mentioned, the combination of increasing glenohumeral abduction and increasing scapular downward rotation is considered a potential contributor to subacromial impingement and rotator cuff pathology.[34-37] The novel finding is that the younger one experienced an SCI, the more likely they were to use these potentially problematic motions as they aged. This is in direct contrast to what would be expected based on shoulder pain findings in adult MWU. Specifically, the adult users with pediatric-onset SCI experience shoulder pain at a lower rate than those with adult-onset SCI, despite greater years of wheelchair use.[3,6,16] This highlights the need to consider additional contributors to shoulder pain and pathology in adult MWU with pediatric-onset SCI. Particularly, morphologic/anatomic adaptations that pediatric MWU can experience during musculoskeletal maturation that users with an adult-onset SCI cannot. The pediatric musculoskeletal system undergoes significant development between the ages of 10 and 21 years old. The scapula and proximal humerus are home to numerous ossification centers where bone growth originates during musculoskeletal development.[23-25] The regulation of this growth is tied closely to the muscular forces exerted on these bones.[39,40] The demands of the shoulder and upper extremity of pediatric users outweigh that of typically developing children, which presents a rich environment for musculoskeletal adaptions. Future work should consider shoulder complex morphology alongside shoulder biomechanics when evaluating contributors to shoulder pain or pathology.

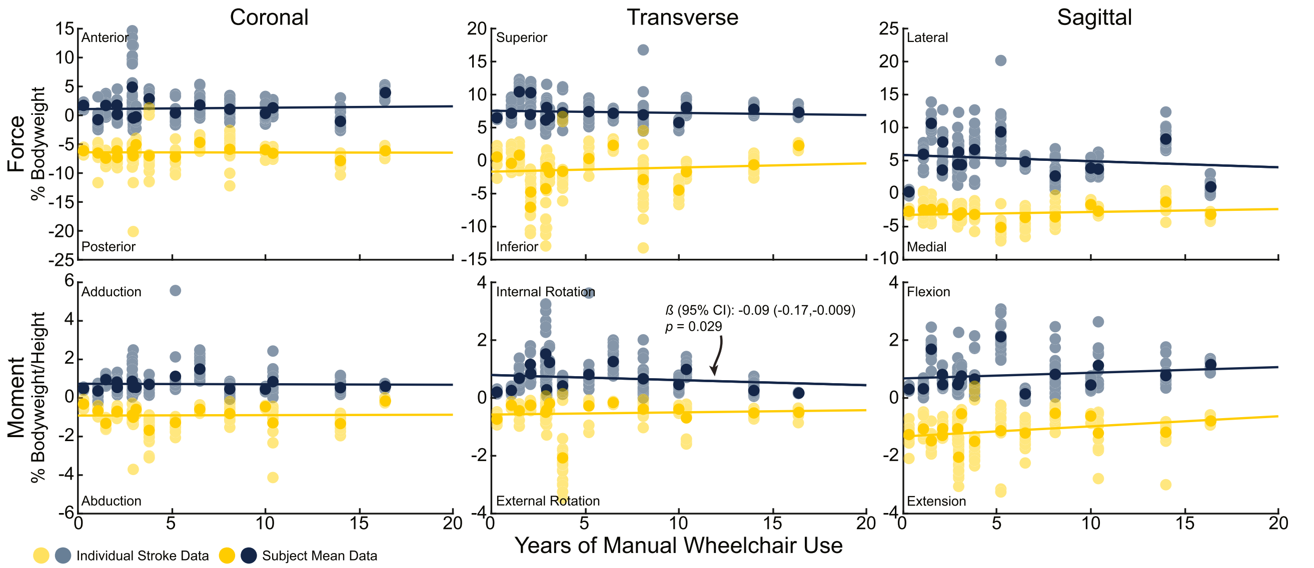

Fig 6 Scatterplots representing the relation between glenohumeral joint forces and moments and years of manual wheelchair use. Maxima/minima glenohumeral forces and moments in each direction of each measurement plane are visualized in blue and gold. Participant means are represented as opaque blue or gold markers, while individual stroke data for each participant are represented as transparent blue or gold markers. Least squares lines of best fit illustrate trends in relation to year of wheelchair use. Significant findings are accompanied by model statistics.

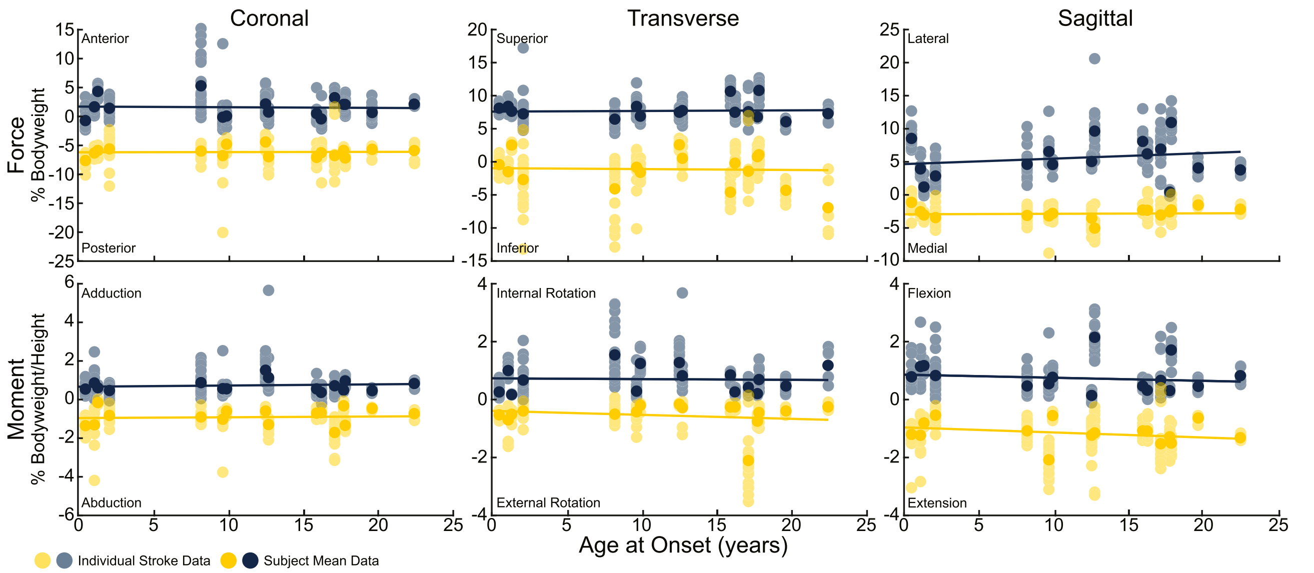

Fig 7 Scatterplots representing the relation between glenohumeral joint forces and moments and age at spinal cord injury onset. Maxima/minima glenohumeral forces and moments in each direction of each measurement plane are visualized in blue and gold. Participant means are represented as opaque blue or gold markers, while individual stroke data for each participant are represented as transparent blue or gold markers. Least squares lines of best fit illustrate trends in relation to age at onset.

We found that glenohumeral joint forces and moments were largely unaffected by age at SCI onset or years of manual wheelchair use. The lone exception was observed in normalized glenohumeral internal rotation moment, which decreased with increasing years of manual wheelchair use. During dynamic activity, the deltoids work synergistically with rotator cuff musculature to stabilize the humeral head in the glenoid.[41-43] Individuals with anterior or multidirectional glenohumeral instability exhibit deficits in internal rotation contributions to shoulder function as measured by the ratio of internal to external rotator strength.[44] An assessment of MWUs with and without impingement syndrome showed that those with impingement exhibited lower internal and external rotation strength.[45] Propelling one's wheelchair with a lower internal rotation moment may contribute to reduced internal rotation strength or reduced internal rotation strength may simply manifest as a decreasing internal rotation moment. Individuals who use a lower internal rotation moment during several thousand manual wheelchair strokes cycles daily[12] may create an imbalance in posterior (infraspinatus and teres minor) to anterior (subscapularis) rotator cuff muscle volume which may contribute to glenohumeral instability and osteoarthritis.[46-48] Yet, this has never been considered in MWUs. Future work that evaluates the relation between shoulder biomechanics and shoulder muscle morphology would provide valuable insight.

Study limitations

The current study had several limitations that must be addressed. Our cross-sectional study design does not account for longitudinal adaptions in shoulder biomechanics. To mitigate this limitation, we used individuals across a range of experimental ages. Nevertheless, group heterogeneity may have influenced our results. Additionally, the participants experienced traumatic or non-traumatic SCIs at a variety of levels between the cervical and thoracic vertebrae. Future work must include larger participant groups so that level of injury and other variables may be controlled for. All participants experienced minimal to no pain at the time of testing, which limits the scope of our findings within the context of pain. Moreover, the visual analog scale does not necessarily reflect pain specific to the shoulder or upper extremity. Our analysis only includes the joints of the shoulder complex because of the ubiquitous nature of shoulder pain in this population. However, MWUs experience elbow and wrist pain as well, and these joints must be considered in future work. Finally, a few significant findings exhibited wide 95% confidence intervals, which may signal some uncertainty about the utility of our findings. We believe that the rigor of the current study, both in its control of relevant variables (age at onset, years of wheelchair users) and the choice of statistical analyses (mixed effects models to account for subject-level variability) offers confidence in our findings. Moreover, our use of normalized dynamics further controlled for variability in participant size.

Conclusions

Our results indicate that a user's age at injury and the years of wheelchair use are associated with shoulder complex biomechanics during wheelchair propulsion. These results are clinically noteworthy, as both age at SCI onset and years of wheelchair use are considered important factors in the incidence of shoulder pain and pathology and often do not linearly relate to one another. While more work is needed to establish the causal relation between shoulder biomechanics during manual wheelchair propulsion and shoulder pain or pathology, our results suggest that biomechanical adaptions over the lifespan and must be considered.

Suppliers

a. SmartWheel; Out-Front, 1826 West Broadway Rd, Suite 43, Mesa, AZ 85202.
b. Vicon Motion Systems; T-Series, Oxford, United Kingdom.
c. MATLAB; MathWorks Inc.

Corresponding author

Joshua Leonardis, PhD, 1225 Discovery Parkway, Suite 131, Wauwatosa, WI 53226 *E-mail address:* leonarj@uwm.edu.

Acknowledgments

The authors would like to thank the staff of the Motion Analysis Center at Shriners Hospital for Children, Chicago for their contributions to this work.

References

1. Brault MW. Americans with disabilities, 2010: Household economic studies. US Department of Commerce, Economics and Statistics Administration, US Census Bureau; 2012.
2. Kaye HS, Kang T, LaPlante MP. National Institute on Disability and Rehabilitation Research. Mobility device use in the United States, 14. Washington, DC: US Department of Education; 2000.
3. Brose SW, Boninger ML, Fullerton B, et al. Shoulder ultrasound abnormalities, physical examination findings, and pain in manual wheelchair users with spinal cord injury. Arch Phys Med Rehabil 2008;89:2086-93.
4. Jahanian O, Van Straaten MG, Goodwin BM, et al. Shoulder magnetic resonance imaging findings in manual wheelchair users with spinal cord injury. J Spinal Cord Med 2020: 1-11.
5. Gutierrez DD, Thompson L, Kemp B, Mulroy SJ. The relationship of shoulder pain intensity to quality of life, physical activity, and community participation in persons with paraplegia. J Spinal Cord Med 2007;30:251-5.
6. Murray C, Zebracki K, Chlan K, Moss A, Vogel L. Medical and psychological factors related to pain in adults with pediatric-onset spinal cord injury: a biopsychosocial model. Spinal Cord 2017;55:405-10.
7. Vogel LC, Chlan KM, Zebracki K, Anderson CJ. Long-term outcomes of adults with pediatric-onset spinal cord injuries as a function of neurological impairment. J Spinal Cord Med 2011;34:60-6.
8. Hoffman MD. Cardiorespiratory fitness and training in quadriplegics and paraplegics. Sports Med 1986;3:312-30.
9. Hwang M, Zebracki K, Chlan KM, Vogel LC. Longitudinal changes in medical complications in adults with pediatric-onset spinal cord injury. J Spinal Cord Med 2014;37:171-8.
10. Slavens BA, Schnorenberg AJ, Aurit CM, Tarima S, Vogel LC, Harris GF. Biomechanics of pediatric manual wheelchair mobility. Front Bioeng Biotechnol 2015;3:137.
11. Soslowsky LJ, Thomopoulos S, Esmail A, et al. Rotator cuff tendinosis in an animal model: role of extrinsic and overuse factors. Ann Biomed Eng 2002;30:1057-63.
12. Boninger ML, Dicianno BE, Cooper RA, Towers JD, Koontz AM, Souza AL. Shoulder magnetic resonance imaging abnormalities, wheelchair propulsion, and gender. Arch Phys Med Rehabil 2003;84:1615-20.
13. Wylie E, Chakera T. Degenerative joint abnormalities in patients with paraplegia of duration greater than 20 years. Spinal Cord 1988;26:101-6.
14. Fullerton HD, Borckardt JJ, Alfano AP. Shoulder pain: a comparison of wheelchair athletes and nonathletic wheelchair users. Med Sci Sports Exerc 2003;35:1958-61.
15. Ustunkaya O, Edeer AO, Donat H, Yozbatiran N. Shoulder pain, functional capacity and quality of life in professional

wheelchair basketball players and non-athlete wheelchair users. Pain Clin 2007;19:71–6.
16. Sawatzky BJ, Slobogean GP, Reilly CW, Chambers CT, Hol AT. Prevalence of shoulder pain in adult-versus childhood-onset wheelchair users: a pilot study. J Rehabil Res Dev 2005;42:1.
17. Mercer JL, Boninger M, Koontz A, Ren D, Dyson-Hudson T, Cooper R. Shoulder joint kinetics and pathology in manual wheelchair users. Clin Biomech 2006;21:781–9.
18. Neer CS. 2nd. Anterior acromioplasty for the chronic impingement syndrome in the shoulder: a preliminary report. J Bone Joint Surg Am 1972;54:41–50.
19. Payne LZ, Deng X-H, Craig EV, Torzilli PA, Warren RF. The combined dynamic and static contributions to subacromial impingement: a biomechanical analysis. Am J Sports Med 1997;25:801–8.
20. Kulig K, Rao SS, Mulroy SJ, et al. Shoulder joint kinetics during the push phase of wheelchair propulsion. Clin Orthop Relat Res (1976-2007) 1998;354:132–43.
21. Ludewig PM, Cook TM. Translations of the humerus in persons with shoulder impingement symptoms. J Orthop Sports Phys Ther 2002;32:248–59.
22. Briley SJ, Vegter RJ, Goosey-Tolfrey VL, Mason BS. The longitudinal relationship between shoulder pain and altered wheelchair propulsion biomechanics of manual wheelchair users. J Biomech 2021;126:110626.
23. Rissech C, Black S. Scapular development from the neonatal period to skeletal maturity: a preliminary study. Int J Osteoarchaeol 2007;17:451–64.
24. Rissech C, López-Costas O, Turbón D. Humeral development from neonatal period to skeletal maturity—application in age and sex assessment. Int J Legal Med 2013;127:201–12.
25. Kothary S, Rosenberg ZS, Poncinelli LL, Kwong S. Skeletal development of the glenoid and glenoid—coracoid interface in the pediatric population: MRI features. Skeletal Radiol 2014;43:1281–8.
26. Sidharthan S, Greditzer HG, IV Heath MR, Suryavanshi JR, Green DW, Fabricant PD. Normal glenoid ossification in pediatric and adolescent shoulders mimics Bankart lesions: a magnetic resonance imaging-based study. Arthroscopy 2020;36:336–44.
27. Hawker GA, Mian S, Kendzerska T, French M. Measures of adult pain: visual analog scale for pain (VAS pain), numeric rating scale for pain (NRS pain), mcgill pain questionnaire (MPQ), short-form mcgill pain questionnaire (SF-MPQ), chronic pain grade scale (CPGS), short form-36 bodily pain scale (SF-36 BPS), and measure of intermittent and constant osteoarthritis pain (ICOAP). Arthritis Care Res 2011;63:S240–52.
28. Schnorenberg AJ, Slavens BA, Wang M, Vogel LC, Smith PA, Harris GF. Biomechanical model for evaluation of pediatric upper extremity joint dynamics during wheelchair mobility. J Biomech 2014;47:269–76.
29. Woltring HJ. A Fortran package for generalized, cross-validatory spline smoothing and differentiation. Adv Eng Softw 1978;1986(8):104–13.
30. Kwarciak AM, Sisto SA, Yarossi M, Price R, Komaroff E, Boninger ML. Redefining the manual wheelchair stroke cycle: identification and impact of nonpropulsive pushrim contact. Arch Phys Med Rehabil 2009;90:20–6.
31. Wu G, Van der Helm FC, Veeger HD, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. J Biomech 2005;38:981–92.
32. Yeadon MR, Morlock M. The appropriate use of regression equations for the estimation of segmental inertia parameters. J Biomech 1989;22:683–9.
33. Nakagawa S, Schielzeth H. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Meth Ecol Evol 2013;4:133–42.
34. Ludewig PM, Reynolds JF. The association of scapular kinematics and glenohumeral joint pathologies. J Orthop Sports Phys Ther 2009;39:90–104.
35. McClure PW, Bialker J, Neff N, Williams G, Karduna A. Shoulder function and 3-dimensional kinematics in people with shoulder impingement syndrome before and after a 6-week exercise program. Phys Ther 2004;84:832–48.
36. Su KPE, Johnson MP, Gracely EJ, Karduna AR. Scapular rotation in swimmers with and without impingement syndrome: practice effects. Med Sci Sports Exerc 2004;36:1117–23.
37. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther 2000;80:276–91.
38. Endo K, Yukata K, Yasui N. Influence of age on scapulo-thoracic orientation. Clin Biomech 2004;19:1009–13.
39. Avin KG, Bloomfield SA, Gross TS, Warden SJ. Biomechanical aspects of the muscle-bone interaction. Curr Osteopor Rep 2015;13:1–8.
40. Frost HM. From Wolff's law to the Utah paradigm: insights about bone physiology and its clinical applications. Anat Rec 2001;262:398–419.
41. Ackland DC, Pandy MG. Lines of action and stabilizing potential of the shoulder musculature. J Anat 2009;215:184–97.
42. Labriola JE, Lee TQ, Debski RE, McMahon PJ. Stability and instability of the glenohumeral joint: the role of shoulder muscles. J Shoulder Elbow Surg 2005;14:S32–8.
43. Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. Clin Orthop Relat Res 1993: 20–8.
44. Warner JJ, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Patterns of flexibility, laxity, and strength in normal shoulders and shoulders with instability and impingement. Am J Sports Med 1990;18:366–75.
45. Burnham RS, May L, Nelson E, Steadward R, Reid DC. Shoulder pain in wheelchair athletes: the role of muscle imbalance. Am J Sports Med 1993;21:238–42.
46. Chalmers PN, Beck L, Miller M, Stertz I, Henninger HB, Tashjian RZ. Glenoid retroversion associates with asymmetric rotator cuff muscle atrophy in those with Walch B-type glenohumeral osteoarthritis. J Am Acad Orthop Surg 2020;28:547–55.
47. Donohue KW, Ricchetti ET, Ho JC, Iannotti JP. The association between rotator cuff muscle fatty infiltration and glenoid morphology in glenohumeral osteoarthritis. J Bone Joint Surg Am 2018;100:381–7.
48. Walker KE, Simcock XC, Jun BJ, Iannotti JP, Ricchetti ET. Progression of glenoid morphology in glenohumeral osteoarthritis. J Bone Joint Surg Am 2018;100:49–56.