Inertial Measurement Unit–Derived Ergonomic Metrics for Assessing Arm Use in Manual Wheelchair Users With Spinal Cord Injury: A Preliminary Report

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Background: Individuals with spinal cord injury (SCI) who use manual wheelchairs (MWCs) have a higher rate of rotator cuff pathology progression than able-bodied individuals. **Objectives:** This study aimed to test the ability of risk and recovery metrics of arm use to differentiate between (1) MWC users with SCI and matched able-bodied participants (cross-sectional matched-sample study) and (2) MWC users with rotator cuff pathology progression over 1 year from those without pathology progression (longitudinal study). **Methods:** Thirty-four MWC users and 34 age- and sex-matched able-bodied individuals were recruited. Upper arm risk (humeral elevation >60°) and recovery (static ≥5 seconds and humeral elevation <40°) metrics were calculated from wireless inertial measurement units (IMUs) worn on the upper arms and torso in the free-living environment. Two separate magnetic resonance imaging studies were completed and assessed for a subset of 16 MWC users approximately 1 year apart. **Results:** The frequency of risk events (p = .019), summated duration of recovery events (p = .025), and duration of each recovery event (p = .003) were higher for MWC users than able-bodied participants. The summated duration of risk events (p = .047), frequency of risk events (p = .027), and risk to recovery ratio (p = .02) were higher and the summated duration of recovery events (p = .036) and frequency of recovery events (p = .047) were lower for MWC users with rotator cuff pathology progression (n = 5) compared to those without progression (n = 11). **Conclusion:** IMU-derived metrics quantifying arm use at postures >60° and risk to recovery ratios may provide insights of potential risk factors for rotator cuff pathology progression. **Key words:** *free-living data collections, humeral elevation, manual wheelchair use, rotator cuff pathology, upper arm posture, wearable sensors*

Introduction

Rotator cuff pathology occurs along a continuum from mild tendinopathy to severe tendon tearing and is commonly found in painful shoulders exposed to overuse.[1,2] Cuff degeneration for those with and without symptoms is considered a normal aspect of human aging.[3] Unfortunately, among persons living with spinal cord injury (SCI) who are dependent on their upper limbs for both mobility and activities of daily living (ADLs), the natural history of pathology progression is accelerated and shoulder pain can develop and become unbearable.[4,5] The accelerated pathology progression among individuals with SCI is theorized to be due to overuse during daily living and manual wheelchair (MWC) use.[6,7] Therefore, identifying metrics that quantify arm use associated with increased rates of pathology progression is an important step to developing mitigating strategies to rotator cuff disease in MWC users.

Both full-time manual workers and individuals living with SCI are at risk of overuse injuries but are dependent on their musculoskeletal health for their livelihood. Therefore, approaches used to investigate and maintain active arm use among manual laborers may be valuable models to understanding risk factors among MWC users. The RAMP II, which assesses musculoskeletal disorder risk factors in industrial occupations, provides thresholds for risk including upper arm postures and recovery

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time that are associated with pain and disorders of the shoulder,[8] such as working with arms in an elevated workspace.[9,10] In a trial that is underway for treating shoulder complaints among a variety of occupational workers, reducing arm elevations >60° was defined as a primary outcome associated with a reduction in shoulder complaints.[10] A >60° threshold was chosen as the focus for the study because limited time was spent in elevations >90° in some of the studied occupations, which is similar to our prior findings of MWC users.[11] Insufficient recovery time during manual labor is also associated with musculoskeletal disorders. The RAMP II identifies sufficient recovery as >90 seconds of rest in 10 minutes of work, with rest periods lasting at least 5 seconds. Applying RAMP II-inspired definitions of arm use to the daily life of MWC users may assist in understanding the mechanisms of increased shoulder pain and pathology observed in this population.

Inertial measurement units (IMUs) are appealing for identifying musculoskeletal risk factors because they can be worn in the free-living environment and capture arm use across a large majority of the day. IMUs have previously been used to quantify wheelchair propulsion behaviors, and we have reported arm elevation daily percentages.[12-14] Although some humeral elevation daily percentage differences were found between MWC users and an able-bodied cohort, analyses such as the one performed for this study are needed to narrow in on metrics that would translate to actionable interventions.

The purpose of this study was to measure arm use with IMUs during the daily lives of MWC users with SCI and matched able-bodied participants. This study aimed to test the ability of risk and recovery metrics of arm use modeled from the RAMP II to differentiate between (1) two cohorts who develop rotator cuff pathology at different rates (MWC users with SCI and a matched able-bodied referent group) and (2) two subgroups of the MWC users (those who exhibited rotator cuff pathology progression over 1 year from those whose rotator cuff imaging findings remained stable). We hypothesized that the MWC user cohort would (1) spend more time in humeral elevation postures >60°, (2) spend less time in recovery (static ≥5 seconds, humeral elevation <40°), (3) have higher frequencies of humeral elevation postures >60°, (4) have lower frequencies of recovery, (5) have longer event durations of humeral elevation >60°, (6) have shorter recovery event durations, and (7) have a larger risk to recovery ratio within a specified short time period (10 minutes) than an able-bodied cohort. We hypothesized similar trends would be seen between the MWC users who exhibited rotator cuff pathology progression over 1 year from those whose rotator cuff imaging findings remained stable. It is important to note that humeral elevation as defined in this study does not account for the plane of humeral elevation. Due to limitations in IMU technology and our data collection protocol, throughout this article, shoulder elevation refers to upward humeral motion in all planes of motion; therefore, shoulder flexion and abduction, for example, are indistinguishable.

Methods

Study participants

This study was approved by the Mayo Clinic Institutional Review Board. Individuals between the ages of 18 and 70 with SCI who use a MWC as their main mode of mobility and sex- and age-matched (±3 years) able-bodied individuals were recruited. Inclusion criteria included functional upper extremity range of motion, defined as active shoulder flexion and abduction of at least 150° and the ability of the participant to touch the opposite shoulder, the back of their neck, and their low back. Participants were excluded if they would not or could not undergo yearly magnetic resonance imaging (MRI) of their shoulders. Participants were also excluded if they self-reported a previous diagnosis of complete supraspinatus tendon tear or if a complete tear was seen during the first MRI. Participants with SCI who had unilateral supraspinatus complete tears were still eligible to be followed for the contralateral shoulder. Additionally, MWC users were excluded if they had health complications that would inhibit their ability to participate in the longitudinal study such as stage IV pressure injuries, extensive comorbidities, or severe pain. Able-bodied individuals were excluded if they had any musculoskeletal or neurological disorder that would have impacted shoulder health or changed their ability to walk independently. To compare between MWC users with and without rotator cuff tendon pathology progression, the data from a subgroup of MWC users who were able to undergo two MRIs, approximately 1 year apart, were used.

Free-living data collections

Participants were provided with wireless IMUs (Opal or Emerald, APDM Inc., Portland, Oregon) and taught how to don the IMUs on each of their lateral upper arms and torso. Data were collected at 128 Hz. Participants were requested to don the sensors in the morning for 2 days, wear them for at least 8 hours, and take them off before going to bed. Additionally, participants were asked to perform a functional calibration at the beginning of each day and after re-donning the sensors.[11, 17] Participants in both cohorts were asked to wear the IMUs during their typical daily routines and not to alter these routines for the sake of the study. The able-bodied cohort did not use wheelchairs or simulate living with an SCI in any way.

Data processing

Acceleration and angular velocity data from the IMUs were used to calculate the orientation estimates. Custom MATLAB (Mathworks, Natick, Massachusetts) code was written to calculate the humeral elevation and static or dynamic status of each arm for each second (**Figure 1**). This process is described in detail elsewhere.[11] In short, the signal magnitude area (SMA) was calculated using the filtered acceleration signal by summing the integration of each axis over each second.[15,16] An SMA threshold (SMA = 0.67 g) to detect static (SMA ≤ 0.67 g) and dynamic periods was calculated as part of a previous study and has been applied to the data in the current study.[17,18] To calculate the humeral elevation angles, the functional calibration was used to align the inertial reference frame with the anatomical axes. The angles between the long axes of the body segments and vertical were defined as the humeral elevation and thorax deviation angles. As the humeral angle was not calculated with reference to the trunk angle, periods

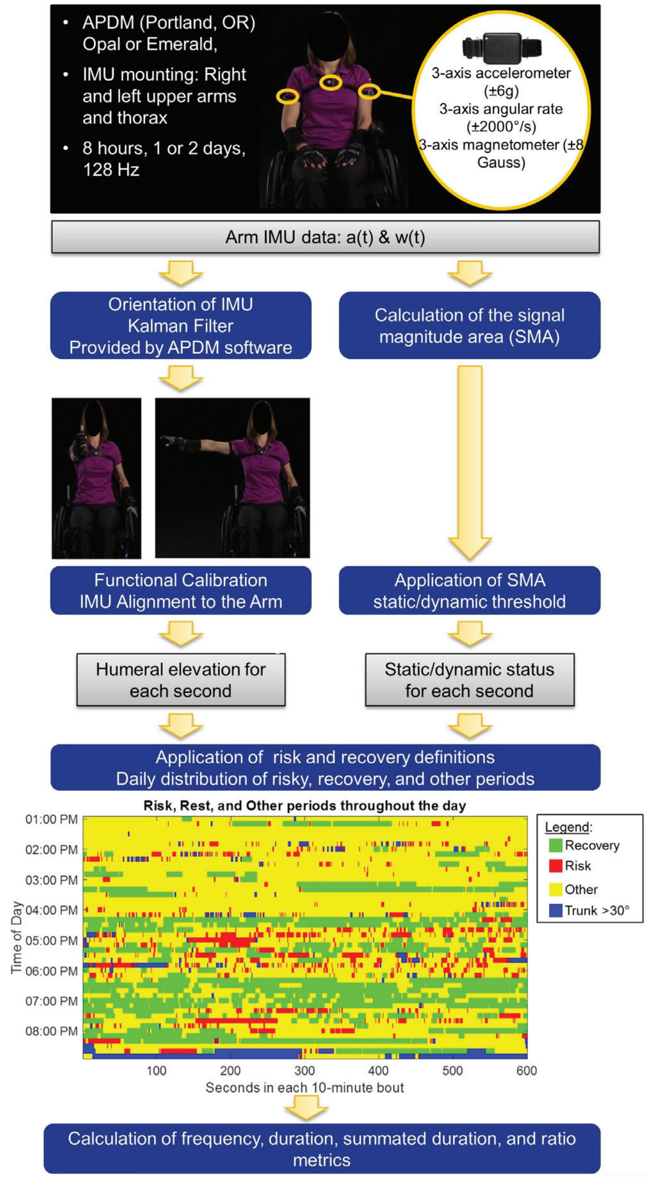


Figure 1. Data processing workflow. Inertial measurement units (IMUs) data were collected on the bilateral arms and torso. The orientation of the IMU was estimated using a Kalman filter and aligned to the body with a functional calibration completed each day. The humeral elevation was then calculated for each second. In parallel, the signal magnitude area (SMA) was calculated from the acceleration data and a threshold was applied to differentiate between static and dynamic periods. Definitions for recovery and risk were applied to the day of data and metrics of frequency, duration, cumulative duration, and a ratio were calculated. Note the individual pictured here is study staff and not a participant in the study.

where the thorax deviation angle were >30° were eliminated.[11,18] The average humeral elevation angle was calculated for each second, with possible angles ranging between 0° (arm down at side) and 180° (arm raised above head).

Risk and recovery metrics

Although we theorize that time spent with arm elevations >60° may be risky to the rotator cuff, this is yet to be proven among MWC users; however, for brevity, in this article we refer to arm positioning above 60° as postures or events of "risk." Likewise, the term "recovery" does not imply physiological "recovery" has definitively occurred.

Risky periods were defined as 1 second or greater of humeral elevation over 60° (static or dynamic), and recovery was defined as at least 5 consecutive seconds of static arm postures at 40° or lower humeral elevations. A static threshold of humeral elevations lower than 40° was chosen to align with the natural resting postures of MWC users and able-bodied participants. Metrics based on frequency, event duration, and summated duration were calculated for each 10-minute period across the full day to align with RAMP II methodology and to improve practical interpretability of the data.[8] Finally, to calculate the ratio of risk to recovery for each 10-minute period, the natural log of the summated risk divided by the summated recovery was calculated. The natural log was used to normalize the data around zero and avoid skewness in the data. For 10-minute periods with only risk, the natural log of the ratio was undefined and therefore it was set to 6.4 (the maximum possible risk value). Similarly, if only recovery occurred in a 10-minute period, the natural log of the ratio was negative infinity and therefore this was set to -6.4. This was not the maximum achievable recovery value; however, this value was still chosen as a way to avoid skewness. If participants provided 2 days of usable data, the average risk and recovery metrics for each day were calculated and then were averaged across the 2 days. A brief description of all risk and recovery metrics are reported in **Table 1**. The requirements for inclusion of IMU data are reported in **Appendix A**.

MRI of the shoulder

Each participant completed two separate MRI studies approximately 1 year apart. Bilateral shoulders of all participants were imaged on GE scanners (General Electric Healthcare, Milwaukee, WI) or Siemens scanners (Siemens Medical Systems, Elrlangen, Germany). All participants were imaged at 3 Tesla. Further details of the protocol can be found elsewhere.[19]

The images were assessed by a board-certified, fellowship-trained, musculoskeletal radiologist with 13 years of experience (N.S.M.).[19] The radiologist was blinded to the study cohorts but not to the prior MRI examinations of each participant in order to access for subtle changes over time as is done in routine clinical care. Tendinopathies were rated as mild, mild-moderate, moderate, moderate-severe, and severe, and tendinopathy scores of 1 to 5 were assigned respectively. Tendon tears were graded as low, intermediate, and high grade partial thickness and full thickness tears, and tear scores of 6 to 9 were assigned respectively. Tendinopathy and tear scores at time 1 and time 2 and the differences between the scores at the two time points were calculated for each rotator cuff tendon (supraspinatus, infraspinatus, subscapularis, and teres minor). Any positive difference in the tendinopathy or tear score on each shoulder (dominant or nondominant) was defined as progression of rotator cuff tendon pathology for that shoulder.

Statistical analysis

To test the hypotheses for the comparisons of the risk and recovery metrics between the MWC cohort and matched able-bodied cohort, Wilcoxon signed-rank tests were used to compare the matched cohorts. To test the hypotheses for the comparisons of the risk and recovery metrics between the MWC users with and without rotator cuff pathology progression, differences between the two subgroups of MWC users were compared using Mann-Whitney U tests. All statistical analyses were completed in SPSS 25, and a p value less than .05 was considered statistically significant. All were reported only for the dominant arm because our previous studies found no differences in pathology and humeral elevation due to hand dominance.[11,19]

Table 1. Risk and recovery metrics description and considerations for metric interpretation

Full name	Short name	Description	Considerations for interpretation
Average summated duration of risk events in the 10-minute periods	Summated duration of risk events	Summated duration of risk events was calculated for each 10-minute period and then the mean value was calculated within a day across all 10-minute periods.	Although a higher value indicates that an individual spent more time in overhead arm elevations throughout their day, this metric does not differentiate between those who had a small number of 10-minute periods with long durations of overhead arm elevation and those who had many 10-minute periods with shorter overhead arm elevation durations. In other words, the distribution of the arm elevations may be very different for individuals with the same value.
Average frequency of risk events per 10-minute periods	Frequency of risk events	Frequency of risk events was calculated for each 10-minute period and then the mean frequency was calculated within a day across all 10-minute periods with at least one risk event (10-minute periods without any risk occurrences were eliminated).	Because 10-minute periods of the day that have no overhead arm elevations were not counted in this metric, a person who had fewer 10-minute periods with overhead arm elevations may have the same value for this metric as a person who had many 10-minute periods with overhead arm elevations. In this example, these two individuals would have different risk of injury even though this value was similar. It is important to consider how many 10-minute periods were included in the calculation (see Table B1 in Appendix B).
Average duration of each risk event in the 10-minute periods	Duration of each risk event	Mean duration of each risk event was calculated for each 10-minute period and then the mean of the mean durations was calculated within a day across all 10-minute periods with at least one risk event (10-minute periods without any recovery risk occurrences were eliminated).	Because 10-minute periods of the day that had no overhead arm elevations were not counted in this metric, two individuals with similar values in this metric may have very different risk of injury. If this value is large, it indicates that when the arm is positioned overhead, it stays overhead for a relatively long duration.
Average summated duration of recovery events in the 10-minute periods	Summated duration of recovery events	Summated duration of recovery events was calculated for each 10-minute period and then the mean value was calculated within a day across all 10-minute periods.	Similar considerations as described in the summated duration of risk events.

Full name	Short name	Description	Considerations for interpretation
Average frequency of recovery events per 10-minute periods	Frequency of recovery events	Frequency of recovery events was calculated for each 10-minute period and then the mean frequency was calculated within a day across all 10-minute periods with at least one risk event (10-minute periods without any risk occurrences were eliminated).	Similar considerations as described in the frequency of risk events.
Average duration of each recovery event in the 10-minute periods	Duration of each recovery event	Mean duration of each recovery event was calculated for each 10-minute period and then the mean of the mean durations was calculated within a day across all 10-minute periods with at least one risk event (10-minute periods without any risk occurrences were eliminated).	Similar considerations as described in the duration of each recovery event.
Average risk to recovery ratio in the 10-minute periods	Risk to recovery ratio	Natural log of the ratio of summated duration of risk events to summated duration of recovery events was calculated for each 10-minute period and then the mean value was calculated within a day across all 10-minute periods.	It is too early to tell which value of this metric is clinically meaningful. A high value may indicate that more recovery is needed during periods with overhead arm use. However, a person with a low value may be too inactive, which is also a risk factor for reduced general and musculoskeletal health.

Note: Risky periods were defined as 1 second or greater of humeral elevation over 60°, and recovery was defined as at least 5 consecutive seconds of static arm postures at 40° or lower humeral elevation.

Results

MWC and matched able-bodied individuals

Thirty-four MWC users and 34 matched able-bodied individuals were enrolled (**Table 2**). Seventeen MWC users and 16 able-bodied participants had 2 days of useable data. Three MWC users and two able-bodied participants only collected 1 day of data. The average (*SD*) number of 10-minute periods with at least one risk event for the MWC users and able-bodied participants was 45 (12) and 44 (10), respectively. More information about the number of 10-minute periods with at least one risk event and number of 10-minute periods without any risk events for the MWC cohort and able-bodied cohort are reported in **Appendix B**.

The results for the risk and recovery metrics (**Figure 2**) indicate that the frequency of risk events (**Figure 2B**; $p = .019$), summated duration of recovery events (**Figure 2D**; $p = .025$), and duration of each recovery event (**Figure 2F**; $p = .003$) were significantly higher in the MWC users than the matched able-bodied participants.

MWC users with and without rotator cuff tendon pathology progression

Sixteen MWC users were enrolled to understand the effects of risk and recovery metrics on rotator cuff pathology progression (**Table 2**). Seven participants had 2 days of useable data. Three participants only collected 1 day of data. The average (*SD*) time between the two MRI visits was 412 (51)

Table 2. Participant characteristics

	First analysis		Second analysis
	SCI ($n = 34$)	Able-bodied ($n = 34$)	SCI ($n = 16$)
Age, years			
Mean (*SD*)	43 (14)	42 (12)	41 (12)
Median (IQR)	38 (31, 55)	38 (32, 54)	37 (31, 55)
Duration of wheelchair use, years			
Mean (*SD*)	12 (12)	N/A	11 (12)
Median (IQR)	5 (3, 21)	N/A	6 (4, 12)
Injury level, *n* (%)			
C6-C8	4 (12%)	N/A	3 (19%)
T1-T8	13 (38%)	N/A	8 (50%)
T9-L1	17 (50%)	N/A	5 (31%)
Sex, *n* (%)			
Female	8 (24%)	8 (24%)	2 (12%)
Male	26 (76%)	26 (76%)	14 (88%)

days and between the initial MRI visit and IMU testing was 81 (123) days. The average (*SD*) number of 10-minute periods with at least one risk event for the MWC users with pathology progression and MWC users without pathology progression was 46 (15) and 50 (13), respectively.

The MRI findings indicated that five participants experienced progression of rotator cuff tendon pathology (progression in tear or tendinopathy score) on their dominant shoulder. The rotator cuff tendon pathologies and tear and tendinopathy scores at time 1 and time 2 for the participants with rotator cuff tendon pathology progression on their dominant shoulder are reported in **Appendix B**. The mean (*SD*) time between the two MRI visits was 1.1 (0.1) years. The results for the risk and recovery metrics (**Figure 3**) indicated that the summated duration of risk events (**Figure 3A**; p = .047), frequency of risk events (**Figure 3B**; p = .027), and risk to recovery ratio (**Figure 3G**; p = .02) were significantly higher in MWC users with progression of rotator cuff pathology than MWC users without progression of pathology. The summated duration of recovery events (**Figure 3D**; p = .036) and frequency of recovery events (**Figure 3E**; p = .047) were significantly lower in the MWC users with progression of rotator cuff pathology.

Discussion

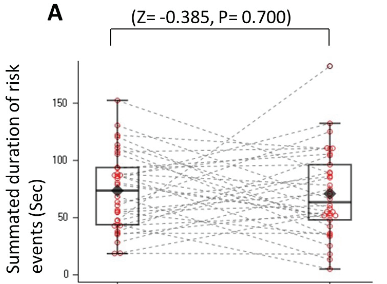
Risk and recovery metrics were investigated to differentiate arm use of MWC users with SCI from a matched able-bodied cohort and compare MWC users with and without rotator cuff pathology progression.

Frequency of the risk events was higher in the MWC users than the able-bodied cohort. Summated duration of recovery events and duration of each recovery event were opposite to our expectations as MWC users spent more time in recovery. Consistent with the hypotheses, MWC users with pathology progression had longer summated durations of risk events, higher frequencies of risk events, shorter summated durations of recovery events, lower frequencies of recovery events, and larger risk to recovery ratios than those without progression.

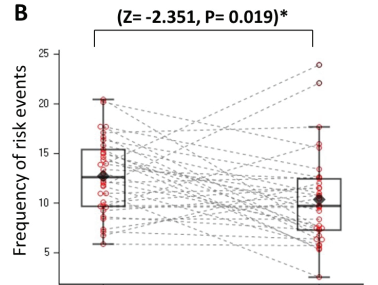
Were measures of risk informative?

It seems intuitive that MWC users with SCI would utilize workspaces requiring higher arm elevation angles than able-bodied individuals to reach things in an environment that was designed for the able-bodied standing adult. In the ergonomic literature, working with the arms in an elevated workspace is a risk factor for shoulder disorders, which we used as a model for our analyses. Although the frequency of risk events was higher for MWC users than the able-bodied cohort, the magnitude of this difference was less than three events per 10 minutes (13 risk events for MWC users compared to 10 for able-bodied cohort). Further research will allow for clinical interpretation of these magnitudes and help determine whether differences measured in short periods of time (10-minute epochs) compound to large exposure differences over years and decades.

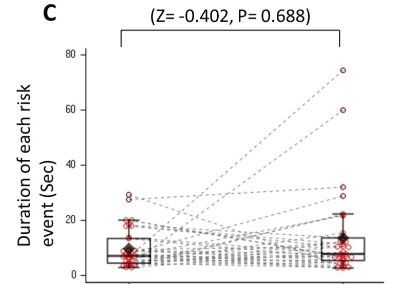
Rotator cuff disease is a multifactorial problem.



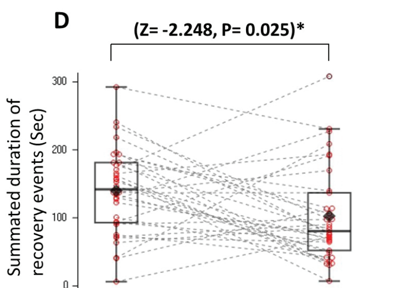
MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
74 (34)	74 (45, 94)	71 (38)	64 (49, 95)



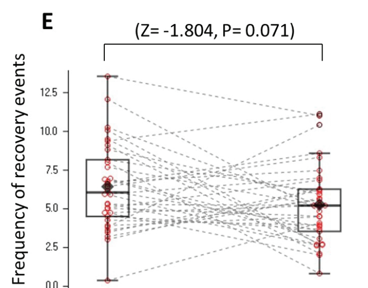
MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
13 (4)	13 (10, 15)	10 (5)	10 (7, 12)



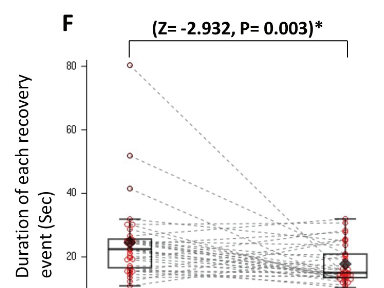
MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
10 (7)	7 (5, 12)	14 (16)	8 (5, 13)



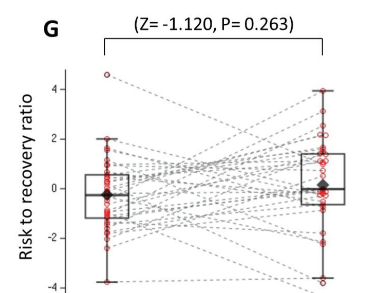
MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
140 (63)	142 (93, 180)	103 (69)	81 (55, 131)



MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
6 (3)	6 (5, 8)	5 (3)	5 (4, 6)

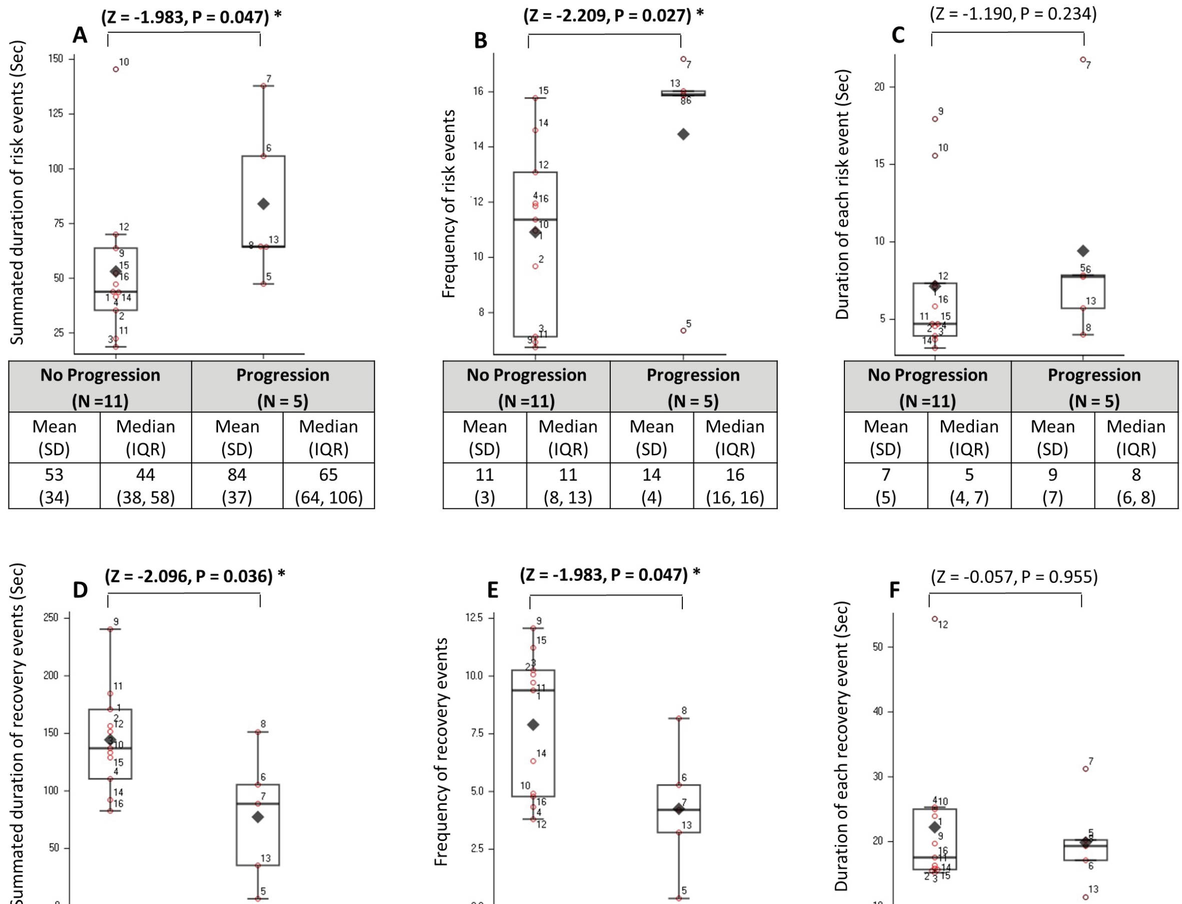


MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
25 (13)	22 (17, 26)	18 (6)	15 (14, 21)



MWC		Able-bodied	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
-0.2 (1.5)	-0.2 (-1.2, 0.5)	0.2 (1.9)	0.0 (-0.6,1.4)

Figure 2. Box plots and data points for the dominant side risk and recovery metrics for the manual wheelchair (MWC) users with SCI (n = 34) and matched able-bodied participants (n = 34). The bottom and top edges of the box indicate the interquartile range between the first and third quartiles (25th and 75th percentiles). The diamond inside the box indicates the mean value. The line inside the box indicates the median value. The value for each participant is shown with a red circle. The dashed lines are connecting the MWC users with the matched able-bodied individuals. Group mean, standard deviation (*SD*), median, and interquartile range (IQR) for each of the risk and recovery metric are reported in separate tables below the box plots and data points graphs. The statistical results for each risk and recovery metric are reported on top of the box plots and data points graphs. An asterisk indicates statistical significance ($p < .05$).



A

No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
53 (34)	44 (38, 58)	84 (37)	65 (64, 106)

B

No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
11 (3)	11 (8, 13)	14 (4)	16 (16, 16)

C

No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
7 (5)	5 (4, 7)	9 (7)	8 (6, 8)

D

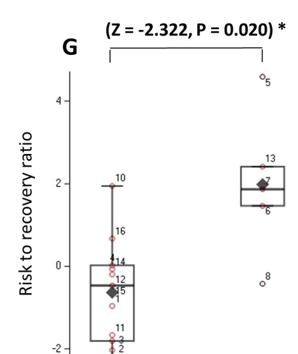
No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
144 (45)	137 (120, 164)	77 (57)	89 (35, 105)

E

No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
8 (3)	9 (5, 10)	4 (3)	4 (3, 5)

F

No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
22 (11)	18 (16, 24)	20 (7)	19 (17, 20)



G

No Progression (N =11)		Progression (N = 5)	
Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
-0.6 (1.3)	-0.5 (-1.7, 0.0)	2.0 (1.8)	1.9 (1.5, 2.4)

Figure 3. Box plots and data points for the dominant side risk and recovery metrics for the manual wheelchair (MWC) users with and without rotator cuff tendon pathology. The bottom and top edges of the box indicate the interquartile range between the first and third quartiles (25th and 75th percentiles). The diamond inside the box indicates the mean value. The line inside the box indicates the median value. The value for each subject is shown with a circle and the corresponding participant number. Group mean, standard deviation (*SD*), median, and interquartile range (IQR) for each of the risk and recovery metric are reported in separate tables below the box plots and data points graphs. The statistical results for each risk and recovery metric are reported on top of the box plots and data points graphs. An asterisk indicates statistical significance ($p < .05$).

The informative value of these data is limited by the exclusion of measurements of forces and moments that contribute to shoulder loading. Measurement of these loads in the free-living environment for an all-day data collection remains a technological challenge and will require advances in technologies such as force sensing gloves, novel algorithms that utilize IMU data to estimate shoulder loads, or novel approaches to identify tasks with known loading profiles.[12,20] Accelerated pathology progression seen among MWC users is also driven by arm use at lower arm elevation levels due to physically demanding tasks such as propulsion and transfers[4,19,21-23]; however, a continued investigation of higher humeral elevation is warranted due to the nature of interacting with the environment from a mostly seated position.[24]

Modifying arm use of MWC users to levels of able-bodied individuals is not feasible due to inherent differences in the way that daily tasks are accomplished. Therefore, there is a clinical interest in characterizing arm use profiles of MWC users whose rotator cuff health remains relatively stable over time. MWC users with pathology progression spent a median of 21 seconds (3% of 10 minutes) more time in humeral elevations >60° and had a 40% greater frequency of risk events (16 events per 10 minutes compared to 11) than those without progression. However, our dataset was small with a short follow-up period (1 year).

Were measures of recovery informative?

Defining possible periods of recovery is less straightforward. Sufficient recovery, following a repetitive or physically demanding task, is needed before the next cycle of that task in order to reduce the risk of injury.[8] The appropriate dosage varies depending on the task. The ≥5-second duration requirement was chosen based on the findings from two previous studies that suggest that very short pauses during repetitive manual tasks do not provide sufficient muscular recovery.[8,25,26] Although informative, these studies utilized small sample sizes (N = 6 and 8), and the tasks were not reflective of MWC users daily tasks. The requirement that static positioning occur at <40° of arm elevation was defined based on the observed natural resting posture of MWC users during the calibration portion of IMU data collection. MWC users' arms are often slightly abducted during natural resting postures due to body habitus and/or wheelchair arm rests. To improve metrics of recovery specific to those living with SCI, research is needed to validate criteria for periods of upper limb muscular recovery during daily activities.

MWC users spent longer time in recovery than the able-bodied cohort, opposite the hypothesis. Interestingly, the median summated duration of recovery for the five MWC users who had pathology progression (90 seconds) was similar to the able-bodied cohort (81 seconds), whereas MWC users without pathology progression had a higher result (137 seconds). More research is needed to understand if there are clinical implications to this result, such as whether MWC users need longer recovery than able-bodied individuals.

Was the risk to recovery ratio informative?

A balanced distribution of recovery and risk is needed to maintain a healthy rotator cuff. The risk to recovery ratio metric aimed to combine both factors. It is important to emphasize that the results for the risk to recovery ratio should be interpreted according to definitions we have for "risk" and "recovery " in this study and the limitations we had in calculating the summated duration of risk and recovery metrics (**Table 1**). The median risk to recovery ratio for the MWC users with pathology progression was positive (1.9); this value was higher than the median ratio (-0.6) for the MWC users without pathology progression. The "considerations for interpretation" column in **Table 1** cautions readers to avoid over-interpretation of these preliminary data; however, differences that we have found between the cohorts and between those with and without pathology progression are suggestive that arm use monitoring in a free-living environment may be able to identify arm use profiles that are protective of accelerated tendon aging. Further research is needed to determine the optimal balance of risk and recovery periods that enable an individual with SCI to maintain a healthy rotator cuff. One future direction that a metric such as this multifactorial ratio could take is to be utilized as a biofeedback index in interventional studies.

In addition to the quantification of arm use metrics during daily life, it will be important for other risk factors to be measured in conjunction with arm use in order to understand the level to which each of these factors contributes to pathology progression. Potentially important risk factors that may also be associated with pathology progression include but are not limited to ergonomic and equipment set up of the home and community environments, biomechanical techniques used to complete tasks (such as wheelchair propulsion and transfers), and factors that influence the structural capacity of the tendon (such as medication use and comorbidities such as diabetes).

Limitations

Due to challenges adjusting for relative drift between the arm and torso IMUs,[11,27] humerothoracic elevation angles and elevation planes relative to the thorax were not calculated in this study. Therefore, 70° of shoulder flexion or abduction would both be interpreted as 70° of humeral elevation and are indistinguishable. Due to participant availability, 1 or 2 days of data were collected for participants, which might not be a reliable representation of their arm use throughout a week.[18,28] Future studies will include more days of IMU data collection. As noted, a larger sample size and longer follow-up are warranted to fully investigate the associations between risk and recovery metrics with the progression of rotator cuff tendon pathology. Finally, the metrics were calculated in 10-minute periods with overhead arm use. Our ongoing investigation of other time periods where work was done at lower elevations will also be informative in understanding risky and beneficial arm use to the rotator cuff.

Conclusion

Measuring the arm use of MWC users with SCI is necessary for future interventional studies to mitigate accelerated degeneration to the rotator cuff. IMU sensors measuring free-living arm use provide insights of potential risk factors for rotator cuff pathology progression. Specifically, metrics quantifying arm use at postures >60° and risk to recovery ratios may provide clinically relevant interventional targets. Additional data collections are warranted to confirm the findings of this study and fully validate definitions of risk and recovery.

Conflicts of Interest

The authors declare no conflicts of interest.

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APPENDIX A

Requirements for Inclusion of IMU Data

Data files were excluded if less than 8 hours of useable data were collected for each day or participants did not complete the daily functional calibration. Further, full days of data were excluded if there was not 6 hours of data where the trunk was under 30° of deviation and arm elevation angles were abnormally high, indicating the participants may have worn or calibrated the sensors incorrectly. Because each day of data was divided into 10-minute periods, data at the end of the day that were not long enough to create another 10-minute period were eliminated from analysis. If only 1 day of usable data existed, metrics were calculated from the single day. If participants provided 2 days of usable data, the data were averaged across the 2 days.

APPENDIX B

Table B1. Number of 10-minute periods with at least one risk event and number of 10-minute periods without any risk events for the manual wheelchair (MWC) cohort, able-bodied cohort, and subgroups of MWC users with pathology progression and without pathology progression

Cohort	No. of 10-minute periods with at least one risk event	No. of 10-minute periods without any risk events
MWC users (*n* = 34)		
Mean (*SD*)	45 (12)	10 (7)
Median (IQR)	44 (38, 54)	7 (5, 14)
Able-bodied participants (*n* = 34)		
Mean (*SD*)	44 (10)	8 (7)
Median (IQR)	45 (37, 50)	5 (3, 11)
MWC users without pathology progression (*n* = 11)		
Mean (SD)	50 (13)	11 (7)
Median (IQR)	54 (42, 57)	8 (5, 17)
MWC users with pathology progression (*n* = 5)		
Mean (SD)	46 (15)	8 (4)
Median (IQR)	39 (37, 53)	10 (7, 11)

Table B2. Rotator cuff tendon pathologies and tear and tendinopathy scores at time 1 and time 2 for the participants with pathology progression on their dominant side

	Participant		**#16**	**#17**	**#19**	**#22**	**#38**
Time 1	Supraspinatus	Tear			Partial tear	Partial tear	
		Tendinopathy		Mild	Mild	Mild	Mild
	Infraspinatus	Tear	Partial tear				
		Tendinopathy	Mild	Mild	Mild		Mild
	Subscapularis	Tear			Partial tear		
		Tendinopathy		Mild-Moderate	Moderate		Mild
	Scores	Tear	6	0	12	6	0
		Tendinopathy	1	4	5	1	3
Time 2	Supraspinatus	Tear		Partial tear	Partial tear	Partial tear	Partial tear
		Tendinopathy	Mild	Mild	Moderate	Mild	Mild
	Infraspinatus	Tear	Partial tear				Partial tear
		Tendinopathy	Mild	Mild-Moderate	Mild	Mild	Mild
	Subscapularis	Tear			Partial tear		
		Tendinopathy	Mild	Mild-Moderate	Moderate		
	Scores	Tear	6	6	12	6	12
		Tendinopathy	3	5	7	2	2

Note: Teres minor is not shown because there were no rotator cuff tendon pathologies for any individuals.