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Accelerometry evaluation of shoulder movement and its association with patient-reported and clinical outcomes following reverse total shoulder arthroplasty

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Background: Accelerometers provide a new method to objectively measure recovery of movement and physical activity in patients following reverse total shoulder arthroplasty (RTSA) and may overcome common limitations associated with patient-reported outcome measures (PROMs). The aim of this study was to assess changes in upper limb movement using accelerometers following RTSA and investigate their association with other clinical outcome measures.

Methods: Thirty-six patients who underwent RTSA wore accelerometers on both wrists and arms for 3 days at 3, 6, and 12 months postsurgery. PROMs (Constant score, American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form, visual analog scale for pain, Single Assessment Numerical Evaluation, Shoulder Activity Level) and isometric shoulder strength were also assessed. Accelerometer outcomes were calculated to quantify counts of forearm and arm activity and the contribution of both arms to activity (limb symmetry and magnitude ratio). Changes and differences in all clinical measures and objective movement measures were evaluated with within-subjects analysis of variance. Correlations between limb activity and other clinical measures were investigated using Spearman correlation coefficients.

Results: Objective movement of the operated arm increased from 3-6 months postsurgery ($P = .004$), but not from 6-12 months ($P = .240$). Limb asymmetries were observed at 3 and 6 months and improved by 12 months postsurgery. No associations were demonstrated between PROMs and objective upper limb movement at 12 months postsurgery.

Discussion: Despite early recovery of function and pain relief assessed by PROMs, objective movement using accelerometers showed delayed recovery of the operated arm postoperatively, before normalizing by 12 months postsurgery. Accelerometers provide a unique insight into functional recovery following RTSA.

Ethics approval was obtained from the St John of God Health Care Human Research Ethics Committee (995) and the University of Western Australia Human Ethics Office (RA/4/1/8533).

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Reverse total shoulder arthroplasty (RTSA) is an increasingly common treatment offered to patients with rotator cuff arthopathy, rotator cuff tears with shoulder pseudoparalysis, or end-stage glenohumeral osteoarthritis. RTSA can improve active shoulder motion, restore functional outcomes, and improve the ability to return to sports and physical activity.[20,21,25] Currently, evaluation of recovery following RTSA is based on patient-reported outcome measures (PROMs) using subjective measures such as questionnaires and pain scores. Although PROMs are inexpensive and easy to administer, they are dependent on patient recall and do not capture detailed functional movement information, nor do they capture efforts made by the patients in moving their shoulder during daily activities.[23] PROMs are also limited by ceiling effects that potentially conceal whether a patient's true level of functioning has been accurately measured.[14,24] In an attempt to overcome these ceiling effects, attention has shifted toward more objective measurements. Although objectively measured strength and range of motion can be obtained easily within a clinical setting, they too fail to measure real world upper limb movement[3] and cannot provide an accurate representation of upper limb function during activities of daily living in a patient's natural living environment.

Accelerometers allow for evaluation of patient function following surgery and have been previously used to analyze the volume and intensity of upper limb movement in patients with rotator cuff tears and after RTSA,[16-18] without the limitation of ceiling effects.[22] Accelerometers are easily attached to the patient and record 3-dimensional (triaxial) accelerations of limb motion that are interpreted as units, or values, of activity. These values have been shown to provide accurate measures of physical activity during walking for patients with previous hip and knee arthroplasties[22] and have a strong relationship with visually observed motions at the shoulder.[19] Measuring the movement and activity profile of patients while they go about their day-to-day activities may provide important information on surgical success and patient function and recovery after surgery beyond that of traditional objective and subjective measures. For example, a progressive increase in activity values in the affected upper limb after surgery may represent an expanding functional profile, whereas a progressive reduction in activity or movement avoidance may be an indication of poor recovery, or developing implant complications, following surgery. These measures of activity also permit comparisons with the nonoperative limb, providing an insight into the magnitude of side-to-side differences and the degree of imbalance between the limbs following surgery.[16] Upper limb symmetry has been proposed as a key variable and one that is useful in research and clinical practice and has previously been used in patients scheduled for shoulder arthroplasty.[16,27]

The primary aim of this study was to evaluate changes in objective upper limb movement and symmetry using accelerometers, from 3-12 months following RTSA. It was hypothesized that objective upper limb movement, assessed using accelerometers, would increase from 3-12 months postsurgery. A secondary aim of this study was to examine the association between objective upper limb movement and PROMs. The secondary hypothesis was that objective upper limb movement of the operated arm would be correlated with patient-reported outcomes of pain and function and objective strength outcomes at 12 months postsurgery.

Material and methods

Study design

A prospective nonrandomized study was undertaken assessing clinical outcomes, including PROMs, isometric strength, and objective upper limb movement using an accelerometer across a 12-month postoperative timeline. Eligible participants were aged 55-85 years, with a diagnosis of a symptomatic rotator cuff tear with pseudoparalysis, glenohumeral joint osteoarthritis, or end-stage rotator cuff arthropathy and were scheduled for RTSA. The exclusion criteria included patients presenting with acute dislocations or undergoing revision surgery. Patients who had undergone prior RTSA, anatomic total shoulder arthroplasty, or a rotator cuff repair within the past 12 months, on either the ipsilateral or contralateral limb, were excluded. Also excluded were patients who had pre-existing conditions associated with upper extremity pain, including that of the contralateral side, and any diagnoses of infection, peripheral nerve compression syndrome, cervical spondylosis, or inflammatory arthritis.

Surgical technique

All patients received RTSA under general anesthesia in a semi–beach chair position with routine antibiotic prophylaxis. A deltopectoral approach was used in all cases, with the subscapularis tendon tagged and mobilized. A limited tenotomy of the superior edge of the pectoralis major tendon was performed for mobilization of the proximal humerus and to improve exposure of the glenoid. All RTSAs were performed using a medial glenoid, lateralized humerus design (Equinoxe Reverse Shoulder Design; Exactech, Inc., Gainesville, FL, USA). The subscapularis was not repaired, as per accepted practice.[11] The long head of biceps was treated by tenotomy at the glenoid margin and tenodesed in the distal bicipital groove. Implant fixation was stable, and the prosthetic joint reduction was stable at the end of the surgical procedure. All patients were prescribed a generic rehabilitation program that incorporated routine passive range of motion (ROM), followed by active assisted and active exercises.

Clinical outcome measures

PROMs were assessed prior to surgery and at 3, 6, and 12 months postsurgery. Included were the American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form; the visual analog scale for pain, where 0 indicates no pain and 10 indicates the highest possible level of pain; and the Single Assessment Numerical Evaluation. The Shoulder Activity Level (SAL) questionnaire was also used to evaluate a patient's level of overall shoulder activity based on the frequency with which he or she completes 5 common activities of the shoulder.[6] Each of the 5 SAL domains are scored from a minimum of 0 points (if a patient answers "never or less than once a month" for all 5 items) to a maximum of 20 points (if the patient answers "daily" for all 5 items).

The Constant score was also employed, which is a 100-point scoring system that includes subjective domains of pain (0-15 points), activities of daily living (0-20 points), pain-free ROM (0-40 points), and an objective measure of maximal pain-free shoulder abduction strength (0-25 points). This strength component of the Constant score was undertaken in patients in an upright position, using the IDO isometer (Innovative Design Orthopaedics, Redditch, Worcestershire, UK). Two trials measuring efforts involving 5-second maximal contractions were completed for both the operated and contralateral side, with the peak value recorded.[30] The Constant score has been demonstrated to be a highly responsive and internally valid outcome tool for use after shoulder arthroplasty, with almost no floor or ceiling effects.[24]

Objective upper limb movement

Objective upper limb movement using an accelerometer was assessed over a 3-day period at 3-, 6-, and 12-month time points following surgery, subsequent to clinical assessments with the surgeon and study investigator. Upper limb movement was measured using wireless activity monitors (Model Link GTX9; ActiGraph, Pensacola, FL, USA) that contained a triaxial accelerometer with a dynamic range of ± 6 gravitational units. The accelerometers were secured bilaterally at the wrists and mid-biceps level of the arm with Velcro straps to capture individual forearm and upper arm segment movements relative to the external environment (Fig. 1). The monitors were sent home with patients at the conclusion of each clinical assessment. To best standardize accelerometer placement across the patient's 2 arms (and across all patients), specific and standardized verbal instruction and an information brochure regarding application, removal, and wear time were provided to all patients. Each morning, participants were instructed to place the monitors on themselves or with assistance from someone in their home if required. Participants were instructed to remove the monitors prior to sleep and before showering. Sensor placement errors were reduced by instructing the participants to place the sensors in the same location during each wear period and properly securing the sensors to the body, so as to not move without body movement.

Accelerations were recorded along 3 orthogonal axes and sampled at 100 Hz. Accelerometry data were downloaded and analyzed using ActiLife 6 software (ActiGraph). The software uses an algorithm that filters the data, eliminating any erratic or nonhuman motions associated with the acceleration signal. Specifically, the data were band-pass filtered between frequencies of 0.25-2.5 Hz followed by removal of accelerations due to gravity, to calculate activity counts. Data counts were sampled as 15-second epochs to provide a mean activity count value per 15 seconds. For each epoch of data, the vector magnitude of the activity counts was calculated to create a single activity value by calculating the square root of the sum of squares from each axis.

Data were considered valid and included in the analysis if the activity monitor had been worn for at least 10 hours for a minimum of 2 of the 3 days.[8] To ensure compliance and inclusion of a data set for analysis, wear time for each participant, for each day, was determined by visually inspecting the data before analysis, excluding prolonged periods of inactivity or nonwear time. The visual inspection ensured that the analysis started after the participants placed the sensors on, and ended before they took them off. In this study, inactivity was defined as a vector magnitude of less than 28 activity counts over a 15-second epoch length, a threshold that was determined from previous studies.[16,17] Accelerometry data were further processed using custom-written code in MATLAB R2018b (Mathworks, Natick, MA, USA), where a mean activity value (m/s2 per 15-s epoch) of the operated and nonoperated limb was calculated for each segment for the 3-day period of interest. Measures of upper limb symmetry, specifically the magnitude ratio[8] and limb symmetry index,[16] were also calculated to assess differences between the operated and non-operated arm (Table I).

Statistical analysis

Analyses were performed using SPSS software (version 26.0; IBM, Armonk, NY, USA), and all tests were 2-tailed with alpha set at $P < .05$. Normal distribution was confirmed using the Shapiro-Wilk test for normality. For aim 1, changes from 3-12 months post-RTSA in mean activity values and limb symmetry measures were evaluated using within-subjects analysis of variance. Post hoc analysis was performed with a Bonferroni test to determine where (if any) differences between individual time points existed. Although not a specific aim of the study, changes over time in PROMs were estimated in the same manner as activity measures to verify improvements for the subsequent aim 2.

To assess the interaction effect of patient demographic variables on objective upper limb activity over time, age, sex, and body mass index (BMI; as a binary variable indicating BMI <30 or >30) were entered separately as independent variables on a 2-way analysis of variance. Similarly, to assess whether participants' limb dominance affected the degree of change in all activity variables over time, an interaction between the operated limb (dominant/nondominant) and time was evaluated. Pairwise analyses were undertaken using independent *t* tests to determine differences in all activity variables at each individual time point.

For aim 2, Spearman correlations were performed for 12-month PROMs (American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form, visual analog scale for pain, Single Assessment Numerical Evaluation, and SAL), the Constant score, isometric abduction strength, and the mean daily objective upper limb movement values for both forearm and upper arm segments during unilateral movement of the operated limb. Correlation coefficients below 0.2 were considered poor, between 0.2 and 0.4 fair, between 0.4 and 0.6 moderate, and scores greater than 0.6 were considered strong.[26]

Results

A total of 36 patients undergoing RTSA, and who met the study criteria, consented to participate in the trial. The cohort comprised 61% women, and the procedure involved the dominant extremity in 64% of cases. Mean age at 12-month follow-up was 73.9 years (range, 56-84 years), with an average BMI of 29.4 (21.0-44.4). Diagnoses were 19 patients (53%) with glenohumeral osteoarthritis, 14 (39%) with rotator cuff arthropathy, and 3 (8%) with a massive rotator cuff tear with pseudoparalysis. Overall, 23 patients (64%) reported returning to the same activity at the same level as prior to surgery, whereas 13 patients (36%) reported returning to the same activity at a different level than prior to surgery.

All PROMs improved from presurgery through to 12 months postsurgery ($P < .001$) (Table II). Similarly, isometric abduction strength improved from 3-12 months postsurgery ($P < .001$) (Table II). Mean activity values increased from 3-6 months for both the upper arm and forearm segments, but not between 6 and 12 months (Table III). Limb symmetry and magnitude ratio all significantly improved from 3-12 months postsurgery (Table III).

Age and BMI variables were found to have no significant effect on any PROM, strength, or activity variable. Isometric abduction strength was greater in male patients than female patients at 12 months postsurgery, as well as at all earlier postoperative time points ($P < .001$) (Table IV). Similarly, mean daily activity counts in the operated arm was greater in male patients than female patients at 12 months postsurgery ($P < .001$) (Table IV), but no differences between sexes were observed at the earlier time points. No differences in PROMs were observed between male and female participants at any postoperative time point.

When including surgery on the dominant or nondominant arm as a between-group factor, although significant time ($P < .001$) and group ($P < .001$) effects were observed for limb symmetry, no interaction effects were observed for the upper arm ($P = .153$) and forearm ($P = .260$), respectively. Similarly for magnitude ratio, for the forearm segment, significant time ($P < .001$) and group ($P < .001$) effects were observed whereass no interaction effects were observed ($P = .435$). Magnitude ratios recorded at the upper arm showed a significant time effect ($P < .001$), whereas no group ($P = .874$) or interaction effects were observed ($P = .856$). Pairwise analyses for measures of upper limb symmetry demonstrated significant differences between the dominant and nondominant limbs for limb symmetry in the forearm at all postoperative time points ($P < .001$) and the upper arm (Fig. 2, A). Similarly, significant differences were observed between the dominant and nondominant limbs for magnitude ratio in the forearm at 3 months ($P = .004$), 6 months ($P > .001$), and 12 months ($P = .006$) and at the upper arm (Fig. 2, B).

Significant correlations were found between the 12-month isometric abduction strength and mean daily activity counts, for both the forearm ($P = .011$) and upper arm segments ($P < .001$) (Table V). No significant correlations were found between PROMs and mean daily activity counts at 12 months postsurgery (Table V). Sex was shown to be—of all patient and clinical variables—the only variable associated (strongly) with upper limb activity ($r = 0.630$, $P < .001$).

Figure 1 Upper limb activity monitor placement.

Table I Objectively measured variables of upper limb activity

Outcome measure	Definition	Calculation
Mean activity value	The intensity of activity across one limb (the operated limb) with values less than 28 activity counts over a 15-s epoch length indicating that no activity occurred.	A mean activity value for the operated limb across 3 d of data collection
Magnitude ratio	The contribution of the operated and nonoperated arms, per each 15-s length of activity. Values of 0 indicate that both upper limbs contribute equally to an activity count. Negative values indicate more nonoperated upper limb activity relative to the operated upper limb, although the opposite is true for positive values.	Dividing the VM of the operated limb by the VM of the contralateral upper limb, for each 15-s bout of activity, and then transformed using a natural logarithm to prevent skewness of positive, untransformed values. Values shown as the median and interquartile range (IQR)
Limb asymmetry	A measurement of the percentage difference between 2 limbs, based on daily mean activity counts. Positive values indicate greater activity in the nonoperated limb, and negative values indicating greater activity in the operated limb. Smaller values represent greater symmetry (perfect symmetry = 0)	If the nonoperated (N) is greater than the operated (O) limb, then: Asymmetry = N / O – 1; If the operated (O) is greater than the nonoperated (N) limb, then: Asymmetry = 1 – O / N

VM, vector magnitude.

Table II Patient-reported outcome measures (mean ± SD) from presurgery to 3, 6, and 12 months postsurgery and within-subjects analysis of variance significance (*P* value)

Variable	Evaluation time point				*P* value
	Presurgery	3 mo	6 mo	12 mo	
Constant score	22.6 (13.7)	58.4 (13.4)	67.3 (11.7)	73.2 (9.9)	**<.001***
ASES	33.6 (17.4)	72.2 (10.9)	80.1 (11.7)	87.5 (9.2)	**<.001***
VAS-P	6.4 (2.1)	1.6 (1.4)	1.2 (1.3)	0.7 (1.0)	**<.001†**
SANE	37.8 (21.6)	73.6 (16.7)	85.1 (10.0)	91.2 (7.9)	**<.001***
SAL	4.8 (4.8)			10.4 (3.8)	**<.001**
Abduction strength		3.2 (1.8)	3.9 (1.9)	4.4 (2.2)	**<.001***

SD, standard deviation; *ASES*, American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form; *VAS-P*, visual analog pain scale; *SANE*, single assessment numerical evaluation; *SAL*, shoulder activity level.
*Significant ($P < .05$) differences between all successive time points.
†Significant ($P < .05$) differences between all successive time points except 3-6 months postsurgery.
Bold indicates $P < .05$.

Discussion

A key finding of this study was that despite patients reporting large and significant improvements in perceived pain, symptoms, and function 12 months after RTSA, these were not correlated with improvements in objective upper limb movement. Continued improvement was observed in both patient-perceived function and objective upper limb movement to 12 months after RTSA. Although improvement in PROMs between all successive time points was observed, no significant improvements were observed in objective upper limb movement from 6 months, which suggests that patients reached an upper limit of desired activity by 6 months postsurgery. This is supported by previous research demonstrating patients following RTSA achieve their majority of improvement within the first 3 months and continue to improve up to and possibly beyond 2 years.[20]

The hypothesis that patient-reported outcomes of pain and function and objective strength outcomes would be correlated with objective upper limb movement for the operated arm at 12 months postsurgery was not supported. Comparisons between PROMs and physical function have shown mixed results in previous studies. Poor associations have been previously reported between patient-reported function and objectively measured strength and ROM after shoulder arthroplasty.[15] Conversely, previous studies have

Table III Objectively measured upper limb activity (mean ± SD) from 3 months to 6 and 12 months postsurgery for the forearm segment and within-subjects analysis of variance significance (*P* value)

Variable	Evaluation time point			*P* value
	3 mo	6 mo	12 mo	
Total wear time, h/d	13.2 ± 1.3	12.2 ± 1.9	11.8 ± 1.8	
Upper arm				
Mean activity value (operated)	238.0 ± 74.0	268.4 ± 79.2	271.3 ± 70.8	**.003***
Mean activity value (nonoperated)	287.9 ± 80.4	300.4 ± 78.4	285.6 ± 77.7	.329
Limb asymmetry	0.25 ± 0.27	0.13 ± 0.25	0.06 ± 0.17	**<.001***,†
Magnitude ratio	−0.47 ± 0.71	−0.24 ± 0.53	0.04 ± 0.60	**<.001***,†
Forearm				
Mean activity value (operated)	513.1 ± 136.2	571.0 ± 146.6	560.0 ± 131.7	**.005***
Mean activity value (nonoperated)	603.3 ± 156.8	626.6 ± 153.9	592.2 ± 162.5	.243
Limb asymmetry	0.20 ± 0.29	0.12 ± 0.25	0.05 ± 0.24	**<.001***,†
Magnitude ratio	−0.30 ± 0.71	−0.09 ± 0.50	0.08 ± 0.55	**.001***

SD, standard deviation.
* Significant ($P < .05$) differences between 3-6 months postsurgery.
† Significant ($P < .05$) differences between 6-12 months postsurgery.
Bold indicates $P < .05$.

Table IV Sex differences for 12-month postoperative upper limb outcome variables (mean ± SD)

Variable	Sex		*P* value
	Male	Female	
PROMS			
Constant score	76.1 ± 12.0	71.3 ± 8.0	.156
ASES	90.9 ± 6.7	85.4 ± 10.1	.077
VAS-P	0.5 ± 0.8	0.8 ± 1.2	.452
SANE	92.0 ± 9.1	91.0 ± 7.3	.824
SAL	11.7 ± 2.9	9.5 ± 4.1	.088
Abduction strength (kg)	6.4 ± 2.0	3.2 ± 1.1	**<.001**
Upper limb activity (m/s^2 per 15-s epoch)			
Mean upper arm activity	326.5 ± 50.5	236.2 ± 58.8	**<.001**
Mean forearm activity	641.1 ± 97.9	508.3 ± 125.6	**.002**

PROMS, patient-reported outcome measures; *SD*, standard deviation; *ASES*, American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form; *VAS-P*, visual analog scale for pain; *SANE*, Single-Assessment Numerical Evaluation; *SAL*, Shoulder Activity Level.
Boldface indicates statistical significance.

reported moderate and strong correlations between PROMS and strength[2,29] and PROMS and ROM.[7]

Accelerometers have gained popularity among researchers who are interested in measuring the volume and intensity of objective upper limb movement and may provide an additional measure of surgical outcome after RTSA. The results from this study are similar to the findings by Hurd et al,[18] who found no associations between patient-reported pain and function, measured via the Disabilities of the Arm, Shoulder, and Hand questionnaire, and objectively measured limb activity from the forearm and upper arm. Although the outcome measures chosen in the present study have previously shown to be valid and reliable in an RTSA cohort, habitual activity in the home and during leisure time assessed using accelerometers may not necessarily be equally representative of function as assessed via these PROMs, which may be a likely explanation for the lack of agreement in this study. Although possessing high validity in terms of patient-perceived function and abilities in performing activities of daily living, PROMs do not assess activity participation, nor the intensity in which patients engage with specific activities. The SAL is the only outcome measure used in this study that possesses a similar construct to upper limb movement using an accelerometer, in terms of frequency of upper limb movement during activities of daily living.

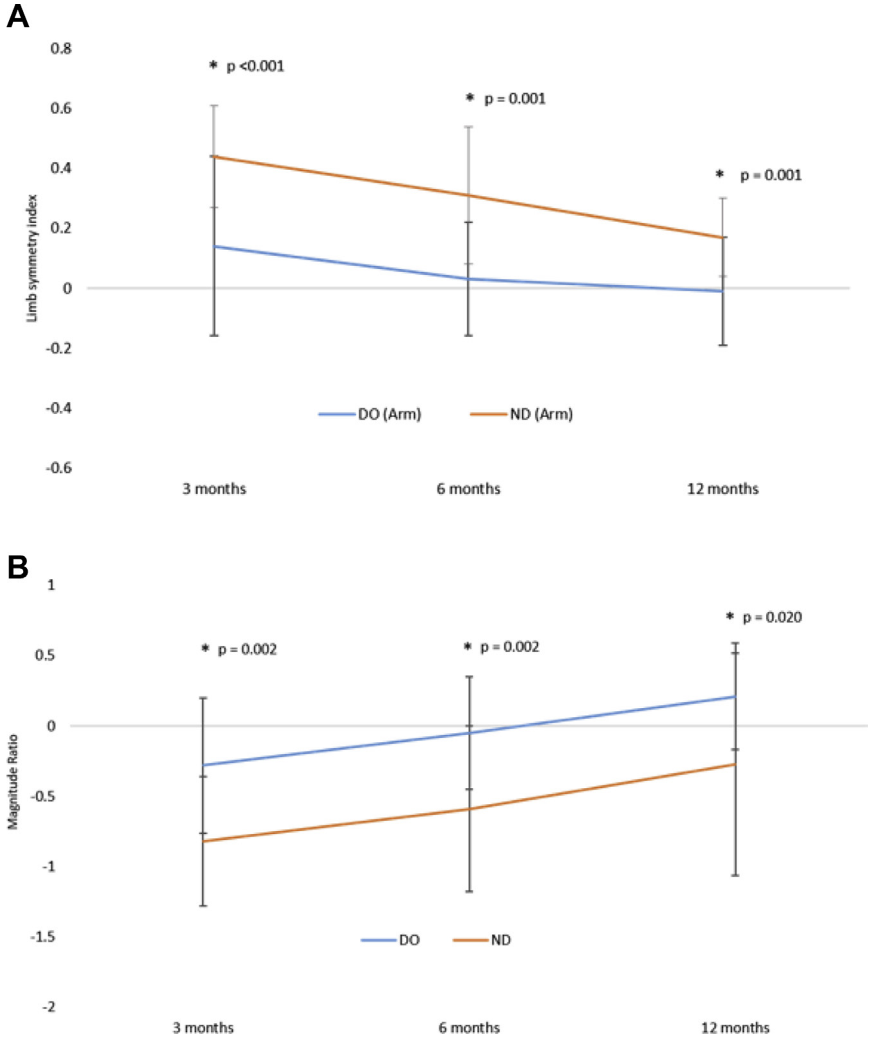

Figure 2 Improvement in (**A**) limb symmetry index and (**B**) magnitude ratio seen from 3-12 months postoperatively. Significant changes between dominant (*DO*) and nondominant (*ND*) extremity are indicated by the *asterisk*.

Table V Spearman correlation coefficients at 12 months postsurgery between objectively measured upper limb activity for the forearm and upper arm segments, and patient-reported outcome measures, including the Constant score, and isometric abduction strength

Upper limb activity	Clinical outcomes					
Variable	Constant score	ASES	VAS-P	SANE	SAL	Abduction strength
Forearm segment, mean activity	0.218	0.258	−0.023	−0.194	0.086	0.418*
Upper arm segment, mean activity	0.278	0.305	0.000	0.040	0.265	0.544†

ASES, American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form; *VAS-P*, visual analog scale for pain; *SANE*, Single-Assessment Numerical Evaluation; *SAL*, Shoulder Activity Level.
* $P = .11$.
† $P < .001$.

In this study, postoperative SAL scores were not shown to be associated with accelerometer-measured activity at 12 months postsurgery. One possible reason for this may be that the SAL contains sports-specific items that would not be relevant to the majority of the patient cohort. Indeed, following RTSA, most surgeons do not allow any participation in activities or sports that are considered high-load (64%) or contact (82%).[13] Although the SAL may accurately describe high-level activities, such as golfing through the item of "swinging motion," no item exists to adequately define gardening or housework, which are considered more moderate activities, and likely more relevant to this patient cohort. Future research should look to investigate the relationship between similar constructs of self-reported physical activity relevant to an RTSA cohort and objective upper limb activity.

Objective upper limb movement using an accelerometer was shown to correlate with isometric abduction strength, which is similar to previous studies. A recent study by Baumgarten et al[5] suggested that improvements in subjective shoulder activity level after anatomic total shoulder arthroplasty may be dependent on improvements in shoulder strength, and although the current study involved RTSA, the findings support this. This is also supported by Wang et al,[29] who found that greater shoulder strength was correlated with patient participation in higher-demand recreational and/or sports activity. Evaluations of postoperative activity and sport levels are generally reported subjectively, and to our knowledge, this study is the first to evaluate the relationship between activity derived from an accelerometer and shoulder strength in an RTSA cohort.

It was hypothesized that objective upper limb movement using accelerometers would increase from 3-12 months postsurgery, and the results of the current study support this. Although improvement in PROMs between all successive time points was observed, no significant improvements were observed in objective upper limb movement from 6 months, which suggests patients reached an upper limit of movement by 6 months postsurgery. This is supported by previous research that has shown that at 6 months postsurgery, patients reach 72%-91% of functional improvement.[20] However, the time required for patients to reach ‘‘maximal’’ recovery has been shown to be variable.[20] The current study's findings support this when assessing improvement by comparing objective upper limb movement of the operated arm against the contralateral side. Limb symmetry indices and magnitude ratios demonstrated clear asymmetry at 3 months postsurgery, suggesting at these time points that the postoperative upper arm is still not moving normally relative to the contralateral limb. Progressive improvements between each successive time points were also observed, suggesting that by 12 months postsurgery the postoperative limb is being used more normally relative to the nonoperative arm. This conclusion is limited by the fact that classifications as to whether an individual has normal or abnormal limb symmetry in the upper limb, captured by accelerometers, is unclear and therefore cannot be clinically interpreted with confidence. However, when comparing our results with a previous study looking at 15 patients before undergoing RTSA and apparently healthy controls,[16] patients exhibited 13% limb asymmetry in the forearm segment, and 17% asymmetry in the upper arm segment, compared with almost no asymmetry in control participants.[16]

Previous studies have investigated hand dominance and its association with clinical outcomes following RTSA, showing postoperative outcomes are equivalent between the dominant and nondominant limbs.[9] In the current study, whether the operated limb was on the dominant or nondominant side had no influence on PROMs, and although there were indeed differences in limb symmetry and magnitude ratio scores at each postoperative time point, no meaningful interactions were observed on the recovery of any objective upper limb movement variable from 3-12 months postsurgery. However, based on whether the dominant or nondominant limb is operated on may be clinically significant. In the current study, those who had RTSA on their dominant side demonstrated 14% asymmetry, and –0.28 in magnitude ratio at 3 months postsurgery. At this time point, the results suggest that patients do not have full functional use of their operated limb. Beyond this time point, for the dominant arm, limb symmetry normalized to 6 and 12 months postsurgery. This information may be useful when counseling patients on expected outcomes, particularly for those who may be concerned about regaining normal shoulder movement or the morbidity associated with operating on their dominant arm.

In the current study, although activity counts were higher in the wrist-worn segment vs. the upper arm placement, we did not observe any differences with respect to recovery of movement or activity across the postoperative timeline between the 2 sensor placements. Wrist-worn accelerometers have been proposed to be a valid position to quantify shoulder activity, with previous studies in healthy populations having reported strong correlations between wrist- and humerus-worn accelerometry.[1] Furthermore, activity counts measured using wrist-worn accelerometers during different shoulder rehabilitation exercises and activities of daily living have demonstrated good sensitivity to detect low-velocity exercises, and showed strong correlations between shoulder motions and activity counts.[19] However, although wrist-worn accelerometers are capable of capturing both arm and forearm movements (ie, gross arm movements), accelerometers placed on the humerus provide a more direct assessment of shoulder activity. Indeed, differences in activity level between wrist- and arm-worn accelerometers have been previously reported,[16] which was also supported in the current study. Therefore, it is still recommended to distinguish accelerometer counts between the upper and lower arm in patients scheduled for, or following, RTSA.

Patient sex was the only demographic variable that was shown to affect strength and objective upper limb movement after RTSA. Male patients demonstrated significantly higher strength scores at every postoperative time point and exhibited greater upper limb activity counts at 12 months postsurgery than females. These outcomes are consistent with a previous study that reported higher function and 12-Item Short Form Survey physical component scores in men over women, despite similar improvements in pain and ROM at 12 months postsurgery.[31] Interestingly, no differences in objective upper limb movement was observed between younger and older patients. Previous research has suggested that patient age greater than 70 years is a significant factor in lower rates of activity.[12] However, it has also been reported that postoperative activity levels are similar between younger and older patients, alongside outcomes of postoperative pain, ROM, and strength.[28] Walters et al[28] assessed patient activity via a self-report questionnaire that was used to stratify the sample into groups of low, moderate, and high demand[32] and found that the level of participation in higher demand activities was equivalent between younger patients (47%) and older patients (47%). Additionally, no differences were observed in patient activity, PROMs, or strength between different categories of age. This study is the first to support these findings via more objective methods of activity measurement. However, future research should study larger patient numbers to investigate the relationship between age and objectively measured physical activity.

Several limitations exist within this study. First, the relatively short follow-up time of 12 months, in a relatively small cohort of patients, may not reflect the outcome scores and activity levels that may be achieved by patients in a longer-term follow-up after RTSA. Second, because of logistic issues and patient convenience, preoperative patient data were only collected for PROMs, with no preoperative activity data, or shoulder strength, undertaken. Objective upper limb movement data taken preoperatively would have provided insight into a patient's shoulder disability before surgery.

To reduce the misclassification error of activity estimates, the current study used a shorter sampling interval of 15-second epochs to provide a mean activity count value per 15 seconds' data. Previous research using upper limb accelerometers for rotator cuff pathologies and following RTSA have used 1-minute epoch lengths,[16-18] whereas others using the same monitors used 1-second epoch lengths.[3,4,19] Although the 15-second epoch length increases the temporal resolution compared with 1-minute epochs, it is also reduced when compared with 1-second epoch lengths. Therefore, it is possible that shorter bursts of activity duration and magnitude were averaged over the 15-second epoch and may have gone undetected. It is also not possible from this study to define specific tasks that were performed by patients outside of self-report. However, previous work has demonstrated validity in using wrist-worn accelerometry to quantify bilateral upper limb activity during the performance of everyday tasks.[4,19] To our knowledge, there is little research that has examined data from accelerometers worn on the upper arm when quantifying performance of everyday tasks, which presents a good opportunity for further research. There are currently no data available to establish the minimal clinically important difference for limb activity captured by triaxial accelerometers. Therefore, it is not known how much improvement in objective upper limb movement is considered clinically meaningful for patients following RTSA and defines good recovery of function. Future research should look to determine the minimal clinically important differences for activity using accelerometers.

Limitations do exist with accelerometers in measuring an individual's function in his or her natural living environment. Although accelerometer-measured activity provides an objective way for evaluating patient function and upper limb movement performance postsurgery, the methods used in this study do not consider the quality of movement including the inability to measure the magnitude of ROM, or plane of motion and velocity.[10] Rather, this study measured the frequency, volume, and intensity of movement using accelerometers in patients following RTSA, to obtain an indication of whether the postoperative limb was being used. Inertial measurement units contain an accelerometer, gyroscope, and magnetometer and have the ability to provide further kinematic insights including angular velocity and limb ROM in an environment outside the clinical setting. However, these additional sensors come with additional challenges, including battery life that is currently not sufficient to collect data beyond 24 hours. The use of inertial measurement units to assess patient function in more detail than just ''activity'' over a longer data capture period would be invaluable and would expand the scope for future research. Lastly, this study has only evaluated accelerometer movement at the lower arm and upper arm and did not take into account or attempt to understand the motion of the scapula during upper arm movements. Furthermore, we were unable to distinguish simultaneous trunk movements that can potentially falsely be detected as arm movements.[10] Although we did use software algorithms to process and filter the data, eliminating any erratic acceleration signals without further kinematic modeling does present the possibility of overestimation of true upper limb activity.

Conclusion

The results of this study demonstrate that improvements in PROMs do not correlate with upper limb movement measured with an accelerometer at 12 months following RTSA. Objective upper limb movement measured using an accelerometer may reflect movement avoidance of the operated limb and/or compensation from the contralateral limb in the early postoperative period, which may normalize by 12 months postsurgery. Accelerometers, although not replacing other clinical measures, have shown to provide a unique insight into functional recovery following RTSA outside of the clinic and are useful as an additional metric when evaluating postoperative recovery.

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