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# Monitoring daily shoulder activity before and after reverse total shoulder arthroplasty using inertial measurement units

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**Background:** The purpose of this study was to use at-home, portable, continuous monitoring technologies to record arm motion and activity preoperatively and postoperatively after reverse total shoulder arthroplasty (RTSA).

**Methods:** Thirty-three patients indicated for RTSA were monitored preoperatively and 3 and 12 months postoperatively. Inertial measurement units were placed on the sternum and upper arm of the operative limb, recording humeral motion relative to the torso for the duration of a waking day. Elevation events per hour (EE/h) > 90°, time spent at >90°, and activity intensity were calculated and compared between time points. Patient-reported outcome measures were also collected at all time points.

**Results:** At 3 ( $P = .040$ ) and 12 ( $P = .010$ ) months after RTSA, patients demonstrated a significantly greater number of EE/h > 90° compared with preoperatively. There were no significant differences ( $P \geq .242$ ) in the amount of time spent at different elevation angles at any time point or in arm activity intensity. Overall, 95% of the day was spent at elevation angles < 60°, and 90% of the day was spent in a low- or moderate-intensity state. Pearson correlations demonstrated relationships between forward elevation and the number of EE/h ( $r = 0.395$ ,  $P = .001$ ) and the number of EE/h > 90° ( $r = 0.493$ ,  $P < .001$ ).

**Conclusion:** After RTSA, patients significantly increase the frequency of arm elevation to higher angles. However, we found no differences in the amount of time spent at different elevation angles. Overall, after RTSA, >95% of the day was spent at elevation angles < 60° and <1% of the day was spent at >90° of elevation.

**Level of evidence:** Level IV; Case Series; Treatment Study

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**Keywords:** Reverse shoulder arthroplasty; inertial measurement unit; wearable sensors; motion tracking; upper extremity; clinical outcomes; shoulder arthritis; cuff tear arthropathy

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Reverse total shoulder arthroplasty (RTSA) is a promising surgical solution for a growing number of pathologies and patient populations, effectively restoring shoulder function and reducing pain.<sup>19,30,32</sup> Postoperative active

range of motion is frequently used by clinicians in evaluating the success of the procedure, although it may not describe the functional range of motion used by patients during activities of daily living. To this effect, the past decade has seen a number of research studies adopting portable at-home technologies for activity monitoring. By eliminating the controlled clinical environment, patient activity patterns may be more accurately represented.<sup>8,20</sup> Inertial measurement units (IMUs), historically used in aircraft navigation applications, have been proposed as a method for accurate, continuous human motion tracking. Composed of triaxial accelerometers, gyroscopes, and magnetometers, IMUs can determine the orientation of a rigid body to within a few degrees.<sup>4,11,21</sup> Unlike optical or electromagnetic tracking, IMUs are cost-effective, portable, noninvasive, and commercially available; do not require an unobstructed line of sight; and are comparably accurate.<sup>2,27</sup>

IMUs have been used extensively to evaluate the lower limb, with a growing interest in their use to evaluate the upper limb.<sup>24,28,34</sup> A handful of studies have applied IMUs to the shoulders of both healthy controls and patient populations, investigating the feasibility of IMU application to the upper limb.<sup>5-7,10,12,14,17,18,29,35</sup> Unlike anatomic total shoulder arthroplasty, for which osteoarthritis is a primary indication, the primary indication for RTSA is cuff tear arthropathy, symptomatically presenting as the inability to actively elevate the arm, in addition to pain.<sup>15,26</sup> For this reason, restoring active elevation to allow patients to independently complete activities of daily living is a primary goal of RTSA.<sup>9,25</sup> To our knowledge, no study has prospectively examined continuous at-home arm motion in an RTSA population preoperatively until the healed phase postoperatively. The purpose of this study, therefore, was to assess operative arm motion and activity preoperatively, during the early healing phase 3 months postoperatively, and at the healed phase 1 year postoperatively in an RTSA patient population. We also sought to determine any relationships between arm activity metrics and clinical outcomes.

## Materials and methods

### Patient selection and instrumentation

This was a prospective case series investigating shoulder elevation prior to and after RTSA as a secondary outcome measure to a randomized trial investigating glenosphere migration between structural bone graft and porous metal augmentation lateralization techniques. A priori power analysis for the randomized trial defined a sample size of 40 participants. Of these, 33 participants (19 men and 14 women; mean age,  $71.2 \pm 8.2$  years) consented to shoulder activity monitoring. The procedures were not consecutive, as primary recruitment was for the randomized trial, and were performed from June 2017 through June 2019. The inclusion criteria were any patient who was scheduled for a primary RTSA and had the capacity to provide written, informed consent.

The exclusion criteria were as follows: patients unwilling to wear the motion-tracking garment; patients requiring revision arthroplasty; patients with insufficient bone stock for either a standard-length cemented or press-fit humeral stem, avascular necrosis, proximal humeral fracture, or cognitive or neurological decline; women who were pregnant or planning to become pregnant, and patients unable to read and/or write English.

All surgical procedures were performed by a single, fellowship-trained orthopedic surgeon (G.S.A.), and all patients received the Aequalis Ascend Flex reverse shoulder system (Wright Medical-Tornier Group, Memphis, TN, USA) with a lateralized glenosphere. Postoperatively, the shoulder was immobilized in a sling for 6 weeks. During this time, passive range-of-motion exercises were performed. Following sling removal, active range-of-motion exercises were initiated. Rehabilitation exercises for strength began 3 months postoperatively, concluding at the patient's discretion.

Approximately 1 month prior to surgery, as well as at the 3-month and 1-year clinical follow-up visits, patients were instrumented with 2 IMUs ( $35 \times 60 \times 15$  mm) to measure shoulder elevation throughout the day. One IMU was positioned at the sternum to provide a reference for the torso's orientation in space; the other IMU, along the lateral shaft of the humerus of the operative shoulder, facing outward. The IMUs were fixed in a snug pocket sewn into a tight-fitting compression shirt (Nike, Beaverton, OR, USA) to inhibit IMU motion relative to the skin while also providing a comfortable solution for long-term wear by the patient. Following instrumentation, patients were encouraged to perform their regular activities of daily living, with the exception of activities that would submerge the IMUs in water (eg, bathing or swimming).

### Data acquisition and analysis

The triaxial IMUs (3-Space Data Logger; Yost Labs, Portsmouth, OH, USA) used in this study have a manufacturer-specified orientation accuracy of  $\pm 1^\circ$  for dynamic conditions along all orientations, with a range of  $360^\circ$  about all axes, and have previously been used in a study investigating shoulder motion.<sup>18</sup> Real-time Kalman filtering was used to determine orientation. An onboard micro secure digital card enabled real-time data logging at a frequency of 10 Hz. An external power supply was connected to each IMU to increase data-logging capacity for the duration of a day of wear. This external power supply was approximately  $40 \times 15 \times 80$  mm and fitted into a separate snug pocket sewn into the compression shirt so as not to inhibit shoulder range of motion. Prior to patient use, IMUs were charged and time synchronized via wired connection to a computer. After the patient donned the compression shirt, a research associate ensured the IMUs were properly positioned. The patient was asked to assume a normal standing position with the arm of interest as close to his or her side as possible. The research associate then began simultaneous data logging from both the torso and humeral reference IMUs. At the end of the day, the patient was asked to remove the instrumented shirt and return it to the research institute via prepaid expedited parcel. The patient was also asked to complete a daily activity log, record when the garment was removed, and include this in the envelope.

On receipt, data from each IMU were uploaded to a personal computer for processing. Output logs from each IMU consisted of time-stamped quaternions: 4-element vectors comprising orientation information in 3 dimensions. Quaternion representations are more robust than traditionally used Euler angles as quaternions do

not suffer from singularities such as gimbal lock when extracting anatomic joint rotations (in the case of 2 rotation axes aligning in a parallel configuration, creating an indeterminate system) and are more memory efficient than logging raw rotation matrices.<sup>2</sup> In MATLAB (The MathWorks, Natick, MA, USA), quaternions from both the torso and humeral IMUs with corresponding time stamps were matched and a rotational difference between sensor pairs was computed with respect to the torso. With the knowledge that the first quaternions were recorded when the patient was in a standing position with the arm at 0° of abduction and neutral alignment, subsequent arm positions can be determined by taking the relative difference in the orientation of the humeral IMU to that of the torso IMU at matched times. Given a quaternion and rotation sequence, anatomic joint angles can then be determined and the angle of interest isolated—in this case, the angle of shoulder elevation.

Following processing, metrics isolated from the data included the number of elevation events per hour; the proportion of time spent within different elevation ranges (0°-20°, 20°-40°, 40°-60°, 60°-80°, 80°-100°, or >100°); the proportion of elevation events that occurred within these elevation ranges; and the intensity of arm activity, rated as low, moderate, or high intensity (defined later). Elevation events were measured as discrete peaks in the time series with a minimum peak height of 20° and minimum peak width of 1 second. Thus, subsequent peaks must be separated by a trough of  $\geq 20^\circ$  to be considered separate events. A peak height of 20° and peak width of 1 second were chosen to highlight arm movements that are deliberate—arm elevation changes of  $< 20^\circ$  and  $< 1$  second are likely normal variations in a static condition that encompass any orientation error from the IMUs and any change in orientation of the IMUs within the compression shirt due to slight body movements.<sup>23</sup> To evaluate the intensity of arm activity, the elevation time series underwent discretization into epochs of 60 seconds.<sup>13</sup> For each epoch, arm activity was classified as low if  $\leq 3$  elevation events occurred; moderate, 4-9 elevation events; and high,  $\geq 10$  elevation events. The number of epochs with low-, moderate-, or high-intensity classifications was normalized to the total number of epochs, defining the proportion of the day spent at each activity level.

## Clinical outcomes

Preoperatively and 3 months and 1 year postoperatively, patients were asked to complete a series of validated patient-reported outcome questionnaires. These included a pain rating from 0 to 10 and the Subjective Shoulder Value; American Shoulder and Elbow Surgeons score; Simple Shoulder Test score; Disabilities of the Arm, Shoulder and Hand score; and Constant-Murley score. Active forward elevation, lateral abduction, and adducted external rotation were measured using a 30-cm manual goniometer. Active internal rotation was recorded as the highest point along the spine attainable with the thumb pointing upward.

## Statistical analysis

Mixed-effects analysis was applied to each clinical outcome and data metric to evaluate any differences between time points, accounting for missing values. Mixed-effects analysis in this instance is analogous to a 1-way repeated-measures analysis of variance with the Tukey post hoc test for multiple comparisons;

however, it is robust to missing values by applying a maximum likelihood model. The maximum likelihood model represents the combination of model parameter values with the highest probability of drawing the provided data sample, assuming that values are missing for random reasons.<sup>22</sup> The effect of arm dominance was also investigated. The Pearson correlation coefficient was assessed to determine any relationships between clinical outcomes and IMU metrics at each time point. Statistical significance was set at  $P < .05$ , and all analysis was completed using Prism software (version 8; GraphPad Software, La Jolla, CA, USA).

## Results

The mean age at the time of surgery was  $71 \pm 8$  years, and 58% of patients were men. In 70% of patients, the arm undergoing RTSA was the dominant arm. Full patient demographic characteristics are reported in [Table I](#).

### IMU data

Preoperatively, 29 patients donned the instrumented garment, with a mean time of wear of 7.1 hours (range, 4.2-13.2 hours;  $>6$  hours in 72%). Three months postoperatively, 27 patients donned the garment for an average of 6.6 hours (range, 1.8-11.2 hours;  $>6$  hours in 74%), and one year postoperatively, 19 patients wore the garment for an average of 5.9 hours (range, 3.7-9.8 hours;  $>6$  hours in 79%). Preoperatively, instrumentation was not performed in 4 patients because their visit to the clinic coincided with further same-day preoperative assessment for which application of the IMUs would hinder appropriate examination. Three months postoperatively, instrumentation was not performed in 6 patients because of unavailability of the study IMU devices, which were all currently deployed owing to a sudden surge in recruitment. One year postoperatively, instrumentation was not performed in 3 patients as a result of contralateral arthroplasty, preventing donning of the over-the-head garment; 2 patients refused

**Table I** Patient demographic characteristics

Characteristic	Data
Age, mean $\pm$ SD, yr	71 $\pm$ 8
Sex: M/F	19/14
Indication	
CTA	14
OA	11
MRCT	4
OA and RCT	3
RA	1
Operative arm: dominant/nondominant	23/10
BMI, mean $\pm$ SD	31 $\pm$ 6

SD, standard deviation; M, male; F, female; CTA, cuff tear arthropathy; OA, osteoarthritis; MRCT, massive rotator cuff tear; RCT, rotator cuff tear; RA, rheumatoid arthritis.

**Table II** Inertial measurement unit data metrics

	Preoperative	Postoperative		P value
		3 mo	1 yr	
No. of elevation events/h	125 ± 53	127 ± 59	150 ± 72	.105
No. of elevation events/h > 90°	5 ± 4	10 ± 8	11 ± 9	.006*
% of time spent at >90° of elevation	0.73 ± 1.24	1.25 ± 1.67	0.78 ± 1.01	.321
% of day spent performing low-intensity activity	62 ± 15	64 ± 15	61 ± 17	.451
% of day spent performing moderate-intensity activity	30 ± 9	27 ± 11	29 ± 10	.592
% of day spent performing high-intensity activity	8 ± 7	8 ± 9	10 ± 11	.360

Data are presented as mean ± standard deviation.

\* Statistically significant ( $P < .05$ ).

**Table III** Proportion of day spent at varying arm elevation angles

Elevation angle, °	Preoperative, %	Postoperative, %		P value
		3 mo	1 yr	
0-20	52 ± 14	55 ± 16	50 ± 15	.496
20-40	31 ± 12	29 ± 11	33 ± 7	.334
40-60	12 ± 8	10 ± 7	13 ± 10	.515
60-80	3 ± 4	4 ± 4	3 ± 3	.890
80-100	1 ± 1	2 ± 3	1 ± 1	.282
>100	0.5 ± 1	1 ± 1	0.5 ± 1	.242

Data are presented as mean ± standard deviation. Percentages may not add up to 100% because of rounding.

further follow-up; and 9 patients were not assessed because of the transition from in-person to remote follow-up resulting from the COVID-19 (coronavirus disease 2019) pandemic.

Three months ( $P = .040$ ) and one year ( $P = .010$ ) postoperatively, patients demonstrated a significantly greater number of elevation events per hour > 90°, approximately doubling the preoperative instance. No other significant differences were observed between time points (Table II). Patients spent the greatest proportion of the day performing low-intensity activity and the least amount of time performing high-intensity activity, regardless of whether they were in the preoperative, early healing, or healed phase of RTSA. One year postoperatively, <1% of the day, on average, was spent at >90° of elevation.

Similarly, no significant differences were observed in the proportion of the day spent within ranges of elevation angles at any time point, with the greatest amount of time spent between 0° and 20° of elevation (Table III) and monotonically less time spent at higher elevation angles (Fig. 1). Considering the peak elevation angle at which elevation events occurred, although not significant for angles between 0° and 80°, there was a trend toward fewer elevation events at lower angles, as well as a greater number of elevation events at higher angles, between the preoperative and postoperative conditions (Table IV,

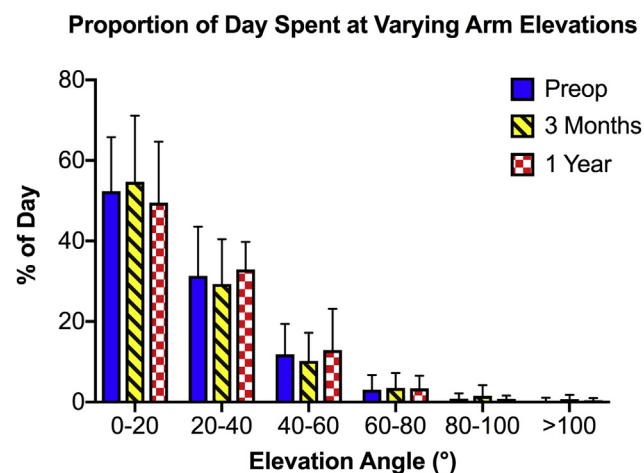
Fig. 2). This was most notable for elevation events > 100°, showing a significantly greater proportion of such events 3 months postoperatively compared with preoperatively ( $P = .020$ ). Although a significant difference in the proportion of elevation events was observed between 80° and 100° of arm elevation, the results were underpowered to detect any significant difference within the multiple comparisons between time points (all  $P \geq .075$ ).

When the results were separated into cohorts based on hand dominance and operative side, the dominant cohort demonstrated significantly more elevation events per hour > 90° and a greater proportion of elevation events > 100° at 3 months (mean difference, 5 [ $P = .043$ ] and 2.6% [ $P = .034$ ], respectively) and 1 year (mean difference, 5 [ $P = .031$ ] and 1.6% [ $P = .045$ ], respectively) compared with preoperatively (Table V). There were no significant differences between time points for any IMU metric within the nondominant cohort (all  $P \geq .200$ ) (Table VI).

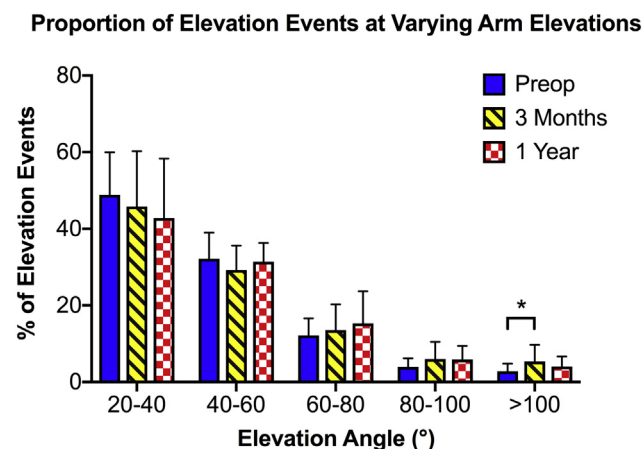
## Clinical outcomes

Patients showed significant improvement in all clinical outcome measures preoperatively through 3 months postoperatively, between 3 months and 1 year postoperatively, and preoperatively to 1 year postoperatively, with the exception of external rotation at all time points and internal rotation preoperatively to





**Figure 1** Binning of elevation angles throughout day preoperatively (*Preop*, solid blue), 3 months postoperatively (*striped yellow*), and 1 year postoperatively (*checkered red*). No significant differences (all  $P \geq .242$ ) were observed within any bin between time points.



**Figure 2** Binning of elevation events preoperatively (*Preop*, solid blue), 3 months postoperatively (*striped yellow*), and 1 year postoperatively (*checkered red*). \*Three months postoperatively, a significantly greater proportion of elevation events occurred at  $>100^\circ$  of elevation compared with preoperatively ( $P = .020$ ).

3 months postoperatively ( $P > .999$ ) (Table VII). The gain in function and reduction in pain between time points were also greater than the minimal clinically important difference for each outcome for which the minimal clinically important difference following RTSA has previously been reported (forward elevation,  $12^\circ$ ; lateral abduction,  $7^\circ$ ; pain rating, 1.6; American Shoulder and Elbow Surgeons score, 13.6; Simple Shoulder Test score, 1.5; and Constant-Murley score, 5.7), with the exception of the pain rating between 3 months and 1 year.<sup>31</sup>

On correlation of clinical outcomes to metrics derived from the IMUs at all time points, maximal forward elevation ( $r = 0.493$ ,  $P < .001$ ) (Fig. 3, a) and lateral abduction ( $r = 0.394$ ,  $P < .001$ ) (Fig. 3, b) were significantly moderately correlated with the number of elevation events per hour  $> 90^\circ$ , as was pain ( $r = -0.347$ ,  $P = .002$ ) (Fig. 3, c). Maximal forward elevation (Fig. 3, d) was moderately associated with the number of elevation events per hour ( $r = 0.395$ ,  $P = .001$ ) and the proportion of the day spent in low ( $r = -0.332$ ,  $P = .004$ ) and high ( $r = 0.347$ ,  $P = .002$ ) activity states (Fig. 3, e). The Subjective Shoulder Value (Fig. 3, f) was weakly though significantly correlated with the number of elevation events per hour  $> 90^\circ$  ( $r = 0.290$ ,  $P = .032$ ) but no other IMU metrics.

## Discussion

The purpose of this study was to investigate the continuous shoulder motion during normal activity prior to, in the early healing phase of, and in the late healing phase of RTSA using IMUs. Characterizing such shoulder motion can provide insight into the effect of shoulder joint replacement on daily living outside the clinical environment. There is a trend toward a greater number of elevation events per hour as the shoulder heals, with significantly more events at higher elevation angles. Extrapolating the daily value of 150 elevation events per hour, assuming a 16-hour waking day, the reverse shoulder undergoes approximately 876,000 cycles per year. Two previously published studies have extrapolated the estimated annual duty cycle of the shoulder using IMUs, ranging from approximately 65,000 to 4.5 million cycles per year.<sup>17,18</sup> Although the presented annual count is within the range of these estimates, variations in

**Table IV** Proportion of elevation events at varying arm elevation angles.

Elevation angle, °	Preoperative, %	Postoperative, %		P value
		3 mo	1 yr	
20-40	49 ± 11	46 ± 15	43 ± 16	.218
40-60	32 ± 7	29 ± 6	31 ± 5	.192
60-80	12 ± 4	14 ± 7	15 ± 8	.206
80-100	4 ± 2	6 ± 5	6 ± 4	.041*
>100	3 ± 2	5 ± 4	4 ± 3	.030*

Data are presented as mean ± standard deviation. Percentages may not add up to 100% because of rounding.

\* Statistically significant ( $P < .05$ ).

**Table V** Dominant-cohort metrics

	Preoperative	Postoperative		P value
		3 mo	1 yr	
IMU data metric				
No. of elevation events/h	128 ± 52	137 ± 58	152 ± 77	.197
No. of elevation events/h > 90°	6 ± 4	11 ± 8	11 ± 9	.012*
% of time spent at >90° of elevation	0.63 ± 0.94	1.29 ± 1.67	0.81 ± 1.12	.255
% of day spent performing low-intensity activity	61 ± 15	62 ± 15	62 ± 17	.677
% of day spent performing moderate-intensity activity	31 ± 9	30 ± 11	28 ± 10	.652
% of day spent performing high-intensity activity	9 ± 7	9 ± 9	10 ± 12	.452
Proportion of day at varying arm elevation angles, %				
0°-20°	54 ± 13	53 ± 16	49 ± 14	.576
20°-40°	29 ± 11	28 ± 9	33 ± 7	.157
40°-60°	12 ± 8	12 ± 7	13 ± 10	.968
60°-80°	4 ± 4	4 ± 4	3 ± 3	.666
80°-100°	1 ± 1	2 ± 3	1 ± 1	.199
>100°	0.5 ± 0.5	1 ± 1	0.5 ± 1	.177
Proportion of elevation events at varying arm elevation angles, %				
20°-40°	48 ± 12	43 ± 14	42 ± 15	.297
40°-60°	32 ± 7	30 ± 7	32 ± 4	.315
60°-80°	13 ± 5	15 ± 7	15 ± 8	.400
80°-100°	4 ± 2	7 ± 5	6 ± 4	.067
>100°	3 ± 2	5 ± 3	4 ± 2	.017*

IMU, inertial measurement unit.

Data are presented as mean ± standard deviation.

\* Statistically significant ( $P < .05$ ).

**Table VI** Nondominant-cohort metrics

	Preoperative	Postoperative		P value
		3 mo	1 yr	
IMU data metric				
No. of elevation events/h	117 ± 61	103 ± 58	143 ± 57	.251
No. of elevation events/h > 90°	5 ± 4	7 ± 6	9 ± 11	.407
% of time spent at >90° of elevation	1.34 ± 1.89	0.75 ± 1.05	0.51 ± 0.55	.656
% of day spent performing low-intensity activity	68 ± 14	72 ± 13	56 ± 14	.224
% of day spent performing moderate-intensity activity	26 ± 9	22 ± 8	33 ± 8	.224
% of day spent performing high-intensity activity	6 ± 7	6 ± 7	10 ± 8	.300
Proportion of day at varying arm elevation angles, %				
0°-20°	46 ± 15	59 ± 17	50 ± 20	.341
20°-40°	39 ± 14	32 ± 15	31 ± 7	.441
40°-60°	11 ± 8	6 ± 4	14 ± 14	.244
60°-80°	1 ± 1	1 ± 1	3 ± 4	.887
80°-100°	1 ± 1	1 ± 1	1 ± 1	.908
>100°	0.5 ± 1	1 ± 1.5	0.5 ± 0.5	.760
Proportion of elevation events at varying arm elevation angles, %				
20°-40°	53 ± 9	52 ± 14	47 ± 20	.679
40°-60°	31 ± 6	28 ± 4	30 ± 8	.251
60°-80°	10 ± 4	11 ± 6	15 ± 9	.200
80°-100°	3 ± 1	4 ± 3	5 ± 4	.426
>100°	3 ± 2	5 ± 6	3 ± 4	.414

IMU, inertial measurement unit.

Data are presented as mean ± standard deviation.

**Table VII** Patient-reported outcome measures

	Preoperative	Postoperative		<i>P</i> value
		3 mo	1 yr	
Forward elevation, °	73 ± 31	98 ± 29	123 ± 18	<.001*
Lateral abduction, °	65 ± 27	90 ± 24	107 ± 24	<.001*
External rotation, °	28 ± 22	29 ± 16	38 ± 17	.059
Internal rotation (1-6) <sup>†</sup>	3 ± 2	3 ± 2	4 ± 1	.001*
Pain score (0-10)	7.1 ± 2.3	2.6 ± 2.1	1.2 ± 1.5	<.001*
SSV (0-100)	33 ± 22	70 ± 20	85 ± 15	<.001*
ASES score (0-100)	34 ± 16	65 ± 17	83 ± 13	<.001*
SST score (0-12)	2.7 ± 2.1	5.2 ± 3.1	8.2 ± 2.7	<.001*
DASH score (0-100)	54 ± 16	41 ± 20	18 ± 17	<.001*
Constant-Murley score (0-100)	28 ± 13	51 ± 16	66 ± 71	<.001*

SSV, Subjective Shoulder Value; ASES, American Shoulder and Elbow Surgeons; SST, Simple Shoulder Test; DASH, Disabilities of the Arm, Shoulder and Hand.

Data are presented as mean ± standard deviation.

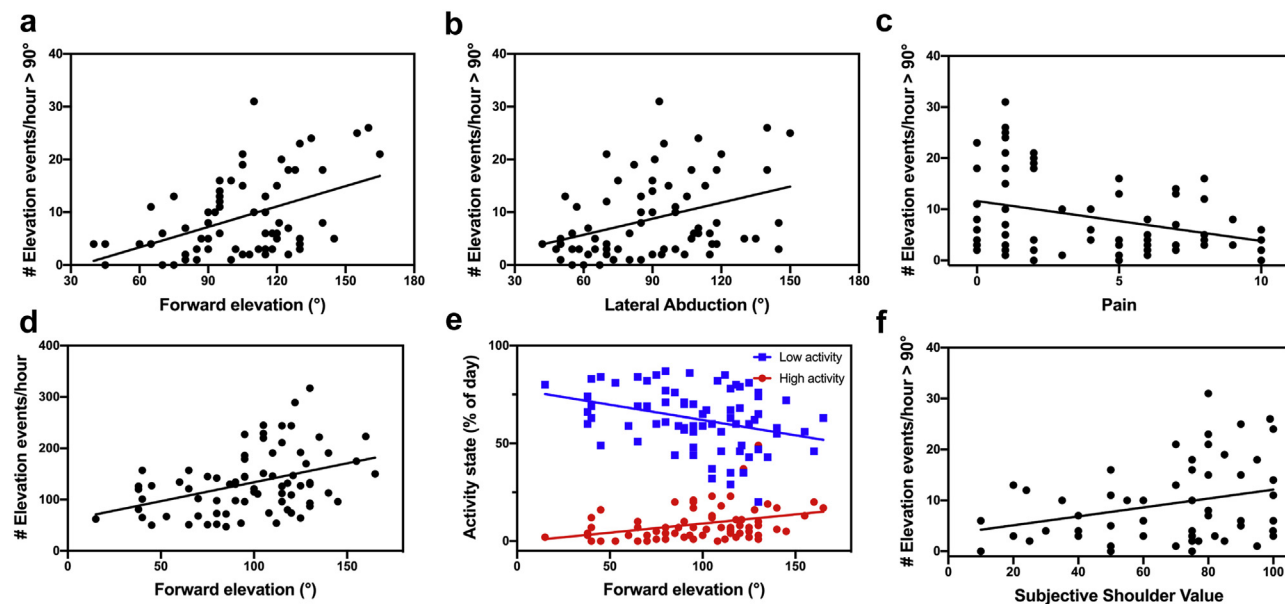
\* Statistically significant ( $P < .05$ ).

<sup>†</sup> Based on landmarks from Constant-Murley shoulder score: 1, lateral thigh; 2, buttock; 3, lumbosacral junction; 4, waist; 5, T12; and 6, T7 or interscapular.

the definition of “motion cycle” ought to be standardized for future further comparison between studies. These values, in turn, can be used in modeling or in vitro kinematics and wear testing to predict implant longevity.

It is interesting to note that there were no significant differences in shoulder activity intensity after RTSA as compared with preoperatively. One would theorize that

after undergoing surgery designed to alleviate pain and improve range of motion, patients would increase their intensity of activity. This finding of no difference may be a reflection of the relatively elderly and obese patient population with limited functional demands, as well as the large standard deviations observed within the group. This may also explain why no differences were observed with respect



**Figure 3** Scatter plots illustrating the relationships between forward elevation and number of elevation events/ per hour > 90° (a), lateral abduction and number of elevation events per /hour > 90° (b), pain and number of elevation events per /hour > 90° (c), forward elevation and number of elevation events per /hour (d), forward elevation and activity state (e), and Subjective Shoulder Value and number of elevation events per /hour > 90° (f).



to the proportion of the day spent at different elevation angles—both preoperatively and 1 year postoperatively, 95% of the day was spent at elevation angles  $< 60^\circ$ . A previous study assessing shoulder biomechanics in the healthy elderly population found similar results, with 97% of the day spent at elevation angles  $< 90^\circ$ , suggesting that even if the elderly population has the capacity to perform activities with a large range of motion, these patients seldom do so.<sup>4</sup> It is also noteworthy that although no differences were observed with time, significantly more elevation events occurred at ranges  $> 100^\circ$  at 3 months postoperatively compared with preoperatively, though not 1 year postoperatively compared with preoperatively. Increases at 3 months are likely a result of patients intentionally completing rehabilitation exercises in an effort to actively improve strength and range of motion. Not surprisingly, the Pearson correlations demonstrated that as active range of motion increased, so too did the number of elevation events per hour, the number of events  $> 90^\circ$ , and activity intensity. The number of elevation events per hour  $> 90^\circ$  was also significantly correlated to the Subjective Shoulder Value, and for this reason, rehabilitation practices following RTSA should continue to focus on improving active range of motion, in particular forward elevation. Overall, it appears that the increased elevation events to obtain motion at 3 months are transient and that patients settle back into their original preoperative movement event frequency.

Assessment of traditional patient-reported outcome measures (PROMs) demonstrated that RTSA is an effective technique for reducing pain and restoring active range of motion and shoulder function as early as 3 months postoperatively, with improved benefit through 1 year. Our outcomes at 1 year are consistent with those reported at a mean 2.8-year follow-up in a cohort with lateralized glenospheres.<sup>1</sup> It is well known that although PROMs can improve the understanding of how a disease or treatment impacts patients' daily lives, patients' emotion, personal bias, missing data, and comorbidities may influence their response.<sup>16</sup> Specifically, the PROMs used in this study were not designed intentionally for elderly patients, and therefore, responses garnering higher scores (eg, the ability to perform a specific activity) may have been selected postoperatively despite patients not actually performing the activity in their normal daily routine. This may have contributed to the subjectively higher PROM scores without an observed change in arm activity.

When considering the effect of arm dominance on IMU metrics, we found that the dominant cohort showed gains at 3 months and 1 year postoperatively in terms of the number of elevation events per hour  $> 90^\circ$  and the proportion of elevation events  $> 100^\circ$  whereas the nondominant cohort presented no observable differences in any metric. A handful of studies have used IMUs to compare the effects of dominance on functional metrics in both healthy and patient populations. In a study evaluating

healthy subjects, Nam et al<sup>23</sup> showed that the working volume of the dominant hand for activities of daily living was significantly greater than that of the nondominant hand. Coley et al<sup>6</sup> reported no significant difference in the frequency and duration of arm positions during daily activities in healthy participants, although there was a trend toward a higher frequency with the dominant extremity. Hurd et al<sup>12</sup> applied a triaxial accelerometer to the upper arms of both a control group and patient group scheduled to undergo shoulder arthroplasty, measuring a difference in activity between dominant and nondominant arms (control), as well as involved and uninvolved arms (patient). They reported that the dominant and uninvolved upper arms showed significantly greater activity. Our results reflect the findings of these studies, suggesting that limb dominance does influence postoperative function.

To our knowledge, this is one of the first prospective studies investigating continuous arm motion in an RTSA patient population, acquiring both clinical outcomes and objective metrics from IMUs. The primary limitations of this study are the patient dropout rate at 1 year—only 14 patients were assessed at all time points—and the short duration of monitoring at each time point. The garment was donned on the same day as clinical follow-up, as many patients resided beyond the study center and did not want to make multiple trips into the city. Consequently, a full day's activities may not be fully represented by the logged data and may also include a period of driving home. To account for missing values at each time point, the mixed-effects model of analysis was used, as is frequently done in the case of analysis of unbalanced repeated measures,<sup>33</sup> although it should be noted that the heterogeneity in wear time at different time points may have affected the results. In particular, this may be responsible for the increase in the number of elevation events  $> 90^\circ$  both 3 months and 1 year postoperatively without an observed increase in time spent at  $> 90^\circ$ . Another explanation for this apparent incongruence is that patients may use their arm more efficiently as a result of both increased range of motion and reduction in pain. Postoperatively, it may take less time to complete overhead tasks than preoperatively, and therefore, more events may take place in the same amount of time.

To ensure there was sufficient space on the onboard secure digital card to record all data, quaternions were logged at a frequency of 10 Hz. Although a higher logging rate would provide a smoother time series, as the study cohort comprised elderly patients, it was proposed that activities would likely not be of very high intensity. This assumption was reflected in the results, showing that approximately 90% of the day was spent in low or moderate activity phases, with  $< 10$  elevation events per minute.

A source of error in the data may have arisen from the use of walking aids, artificially increasing the duration spent at higher elevation angles, such as in the case of a

walker. Another source of error is motion artifact of the garment while it is worn. Although a tight-fitting shirt was chosen for each patient, it is possible for the position of the IMUs relative to the humerus and torso to shift slightly during the day. The calibration procedure also may have led to an underestimation of elevation angles. When the closest position of the arm to the body in adduction is taken as 0° of elevation, patients with more adipose tissue and associated adduction deficit would record fewer data points at higher elevation angles than patients without this adduction deficit.

Another limitation of this study is that the IMUs were not specifically validated against optical tracking techniques. A previous study by El-Gohary and McNames<sup>10</sup> compared the use of IMUs with an unscented Kalman filter sensor fusion orientation estimation algorithm vs. 3-dimensional optical tracking for upper-extremity motion with human subjects. They demonstrated a root-mean-square angle error < 8° and average correlation coefficient ( $r$ )  $\geq 0.95$  between the 2 tracking techniques, showing good reliability and validity for the use of IMUs in upper-extremity motion tracking. This error is greater than the manufacturer-specified accuracy of  $\pm 1^\circ$  and likely more representative of organic human movement. Future studies ought to validate the use of their sensor techniques prior to clinical application.

Moreover, future studies should consider standardizing data acquisition and analysis methods to facilitate comparison between studies and identify metrics of clinical importance. They could also investigate the effect of sex, different planes of motion, and the angle at which intentional arm movements occur using the results from healthy age-matched controls to provide targets for rehabilitation practices.

Overall, IMUs provide an objective measure of patient arm use and activity. With an increasing number of studies reporting objective measurements following joint replacement, there is the potential to define their typical post-operative performance. This may help patients establish a realistic set of expectations following the procedure, which in turn may decrease the risk of patient dissatisfaction.<sup>3</sup> The application of IMUs can be extended to the assessment of different shoulder pathologies and treatments, complementing the clinician's assessment and addressing the limitations of PROMs. Taken together, objective and subjective measurements, in addition to the degree to which patient expectations have been met, can help define a successful procedure.

## Conclusion

After reverse shoulder arthroplasty, patients significantly increase the frequency of arm elevation events to higher elevation angles. However, we found no differences in the amount of time spent at different elevation angles when comparing preoperative with postoperative data.

Overall, after RTSA, >95% of the day was spent at elevation angles < 60° and <1% of the day was spent at >90° of elevation.

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