J Shoulder Elbow Surg (2019) 28, 1505–1514

ELSEVIER

JOURNAL OF SHOULDER AND ELBOW SURGERY

www.elsevier.com/locate/ymse

Continuously monitoring shoulder motion after total shoulder arthroplasty: maximum elevation and time spent above 90° of elevation are critical metrics to monitor

Ryan M. Chapman, PhD[a,*], Michael T. Torchia, MD[b], John-Erik Bell, MD[b], Douglas W. Van Citters, PhD[a]

[a]*Thayer School of Engineering, Dartmouth College, Hanover, NH, USA*
[b]*Department of Orthopaedics, Dartmouth-Hitchcock Medical Center, Lebanon, NH, USA*

Background: Traditional clinical shoulder range-of-motion (ROM) measurement methods (ie, goniometry) have limitations assessing ROM in total shoulder arthroplasty (TSA) patients. Inertial measurement units (IMUs) are superior; however, further work is needed using IMUs to longitudinally assess shoulder ROM before TSA and throughout post-TSA rehabilitation. Accordingly, the study aims were to prospectively capture shoulder elevation in TSA patients and to compare the results with healthy controls. We hypothesized that patients would have reduced maximum elevation before TSA compared with controls but would have improved ROM after TSA.
Methods: A validated IMU-based shoulder elevation quantification method was used to continuously monitor 10 healthy individuals (4 men and 6 women; mean age, 69 ± 20 years) without shoulder pathology and 10 TSA patients (6 men and 4 women; mean age, 70 ± 8 years). Controls wore IMUs for 1 week. Patients wore IMUs for 1 week before TSA, for 6 weeks at 3 months after TSA, and for 1 week at 1 year after TSA. Shoulder elevation was calculated continuously, broken into 5° angle "bins" (0°-5°, 5°-10°, and so on), and converted to percentages. The main outcome measures were binned movement percentage, maximum elevation, and average elevation. Patient-reported outcome measures and goniometric ROM were also captured.
Results: No demographic differences were noted between the cohorts. Average elevation was not different between the cohorts at any time. Control maximum elevation was greater than pre-TSA and post-TSA week 1 and week 2 values. Time under 30° and time above 90° were equal between the cohorts before TSA. After TSA, patients showed decreased time under 30° and increased time above 90°.
Discussion: This study demonstrates that acute and chronic recovery after TSA can be assessed via maximum elevation and time above 90°, respectively. These results inform how healthy individuals and patients use their shoulders before and after TSA.
Level of evidence: Basic Science Study; Kinesiology

Keywords: Arthroplasty; shoulder; inertial measurement unit; rehabilitation; range of motion; wearable

For this prospective nonrandomized study, institutional review board approval was granted by Dartmouth College (No. STUDY00028846).

*Reprint requests: Ryan M. Chapman, PhD, Thayer School of Engineering, Dartmouth College, 14 Engineering Dr, Hanover, NH 03755, USA.
E-mail address: rmchapman.th@dartmouth.edu (R.M. Chapman).

1058-2746/$ - see front matter © 2019 Journal of Shoulder and Elbow Surgery Board of Trustees. All rights reserved.
https://doi.org/10.1016/j.jse.2019.01.003

Total shoulder arthroplasty (TSA) is often the end-stage treatment for glenohumeral osteoarthritis. Although TSA occurs less frequently than other joint replacement procedures (approximately 30,000 vs. approximately 1 million total hip and knee arthroplasties),[9] it is the fastest growing total joint replacement procedure in the United States, with a reported increase of 67% during a recent 5-year period.[11] Although TSA use is rapidly increasing, a dearth of data exists regarding shoulder range of motion (ROM) outside of well-controlled clinic and laboratory environments in patients undergoing TSA. Maximum ROM captured by the operating surgeon at prescribed intervals in the clinical setting is a standard and traditional metric used to objectively assess shoulder function both before and after surgical intervention.[6,14,16,20,21,27,37] Although often used as the "gold standard," clinical maximum shoulder ROM likely does not realistically encapsulate ROM use or function during activities of daily living (ADLs) in patients' home environments. In short, although clinical interventions should attempt to restore normal motion including high humeral elevation (>150°), a patient who achieves a large ROM in the clinic may not use the full range of that motion during typical daily activities. In other words, we want to ensure that patients can both reach above their head when necessary (eg, reaching a coffee cup in a cabinet) and use the entire ROM as frequently as desired.

Several groups have identified shoulder elevation as the most critical metric for completing the majority of ADLs.[4,25] Not only is it critical for accomplishing ADLs, increasing shoulder elevation ROM is one major focus of post-TSA physical therapy.[3] However, methods for assessing shoulder elevation ROM before and after surgical intervention remain cost prohibitive and time-consuming and lack scalability (eg, optical motion capture or fluoroscopy).[5,15,22,33,40] As such, measurement methods for capturing shoulder ROM that are lower cost, timely, and scalable are necessary. A method that fulfills these goals is inertial measurement units (IMUs). Specifically, IMUs provide improved accuracy (approximately 1° vs. 5°), allow continuous rich data capture (acceleration, velocity, and joint angles vs. singular discrete maximum ROM), and cost less to implement in the United States ($150 vs. $2100 for entire postoperative measurement set)[18,29] than traditional ROM measures such as goniometry. IMUs capture linear acceleration, angular velocity, and magnetic field strength to facilitate computation of the 3-dimensional orientation of each IMU and, in the case of multiple IMUs, the angles between them. Using IMUs to capture shoulder ROM has been attempted, yet the majority of work has focused on increasing measurement precision.[10,24] However, Chapman et al[8] developed, validated, and deployed an IMU-based measurement method that captured shoulder ROM in healthy elderly individuals continuously (8-12 h/d) for long durations (weeks at a time). They found that although healthy individuals can achieve high maximum ROM (approximately 170° of elevation), these individuals seldom use that ROM (97% with <90° of elevation). However, their study did not explore arthroplasty patient populations.

Accordingly, the goals of this work were to complete a prospective analysis of shoulder elevation in patients undergoing TSA using the methods described by Chapman et al[8] and to compare the results with individuals with no shoulder pathology. We hypothesized that patients would have reduced maximum elevation (<150°) prior to surgery compared with controls.[7,30] In addition, we hypothesized ROM would improve in patients after TSA and would equal that of control subjects.[23,30]

Materials and methods

We performed a prospective nonrandomized study assessing shoulder elevation recovery after TSA. The method used in this study was described in detail by Chapman et al.[8] In brief, IMUs (APDM, Portland, OR, USA) were rigidly affixed to the sternum (xiphoid process) and humerus (deltoid tuberosity) (Fig. 1, *A*). Sensors were temporally synchronized throughout each day, both sensor data streams were converted to independent 3-dimensional vectors, and an angle (shoulder elevation) between the respective sensors was computed (Fig. 1, *B*). Each day, subjects followed a prescribed daily workflow (Fig. 2) wherein they awoke, removed the IMUs from the charging dock, and donned the IMUs. Sensors then automatically synced via a meshed local area network through "sync packet" comparison of respective clocks. After synchronization, continuous data capture (8-12 h/d) and local data storage occurred on the respective IMUs. On-board 16-GB microSD cards and high-capacity lithium-ion polymer batteries allowed daily captures up to 18 hours for up to 60 days. At the end of each day, subjects doffed the IMUs and re-docked them, terminating the daily capture and allowing the IMUs to recharge. This process was repeated daily for the duration of the study, and sensors were returned to the study team for analyses. Finally, data were downloaded and processed offline.

Statistical analyses performed a priori determined that the minimum sample size requirement for each cohort ($\alpha = .05$, power of 0.80) should be 9 subjects. As such, a prospective analysis was conducted on 10 healthy individuals (4 men and 6 women; mean age, 69 ± 20 years) with no known shoulder dysfunction and 10 patients (6 men and 4 women; mean age, 70 ± 8 years) undergoing TSA. Controls were enrolled from a local retirement community (with the inclusion criterion being the ability to clinically achieve full forward flexion [>150°], extension [>40°], abduction [>130°], external rotation [>90°], and internal rotation [>60°][4]; no neuromuscular or musculoskeletal disease impacting the upper extremities; and no terminal illness expected to result in death within 1 year of enrollment). After consent and enrollment, control handedness was captured using the Edinburgh Handedness Inventory[28] to determine on what arm the IMUs would be donned. Control subject clinical goniometric ROM (forward flexion and external rotation) and patient-reported outcome measures (PROMs) were then captured, including pain, the American Shoulder and Elbow Surgeons (ASES) survey, and the Patient-Reported Outcomes Measurement Information System (PROMIS)–10 mental component summary (MCS) and physical component summary (PCS).[17,26] Patients were enrolled from a

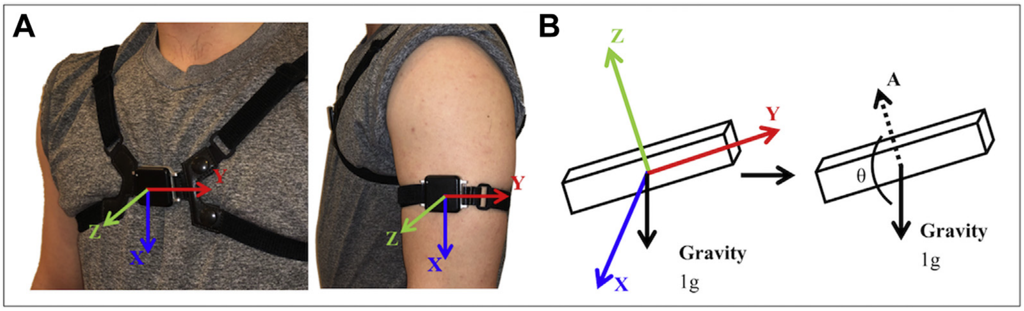

Figure 1 Example of instrumentation including inertial measurement unit–donning locations on sternum and humerus (**A**) and angle computation between gravity and acceleration data (**B**).

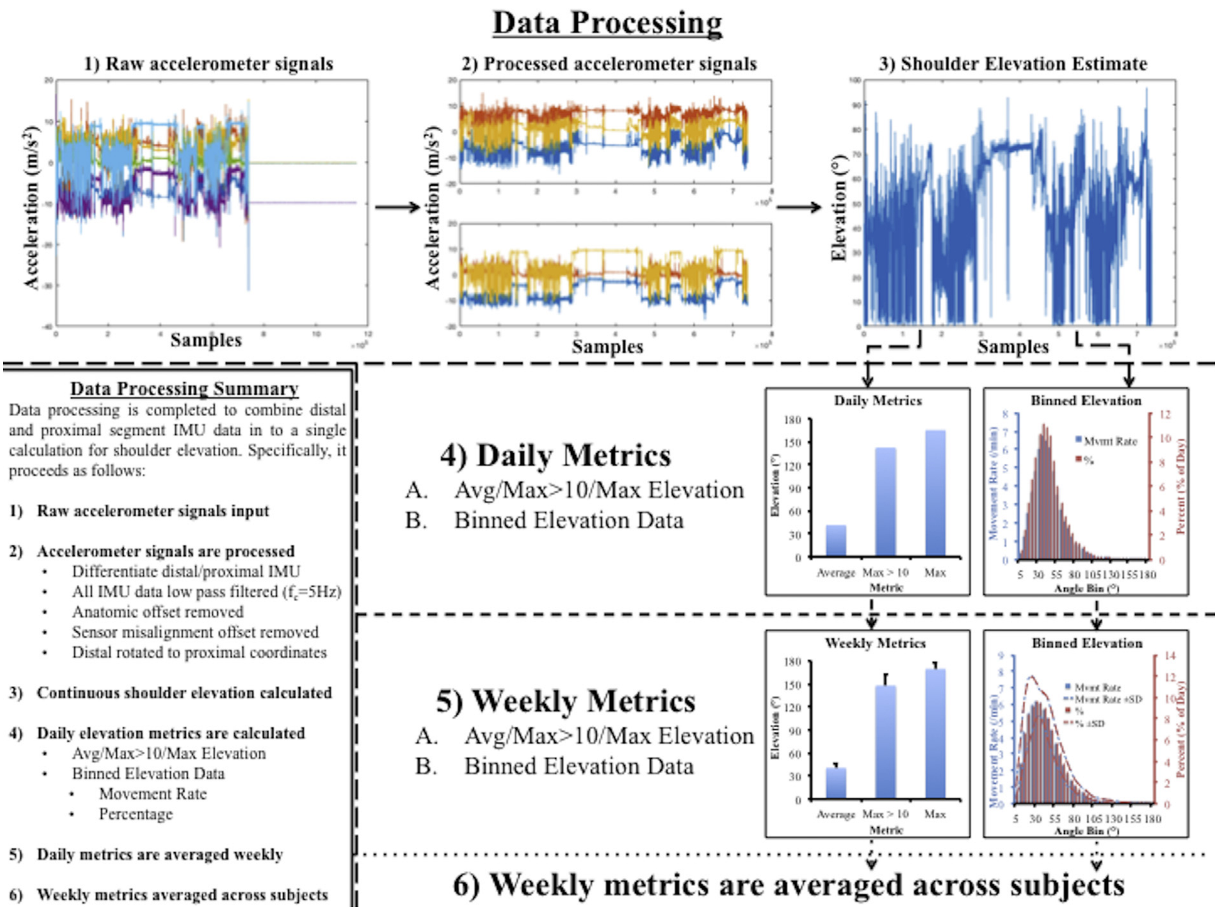

Figure 2 Data processing workflow including (1) raw accelerometer signal input; (2) processing accelerometer signals (bony segment differentiation, low-pass filtration, offsetting anatomic/sensor misalignment, and distal-to-proximal coordinate transformation); (3) continuous shoulder elevation calculation; (4) daily metric calculation (average [*Avg*], maximum [*Max*] bin > 10×, maximum elevation, binned movement rate, binned percentage); (5) weekly metric averages; and (6) total subject averages. *IMU*, inertial measurement unit; *SD*, standard deviation.

single surgeon's consecutive caseload (with the inclusion criterion being presentation for unilateral TSA resulting from primary osteoarthritis, no other neuromuscular or musculoskeletal disease impacting the upper extremities, and no terminal illness expected to result in death within 1 year of enrollment). After consent and enrollment, handedness was captured for patients (Edinburgh Handedness Inventory[28]) for correlation analyses. Clinical ROM and PROMs listed earlier were then captured from pre-TSA patients.

All subjects participated in a sensor-use tutorial (approximately 30 minutes); this included plugging charging docks into a standard 60-Hz/120-V alternating-current wall outlet, placing IMUs on charging docks, donning IMUs (where and how each IMU was worn on each bony segment), and instructions on the duration of use. Subjects asked questions throughout the tutorial and were given an instruction manual with contact information for post-tutorial questions. Controls wore IMUs as noted previously on their dominant arm (Edinburgh Handedness Questionnaire[28]) and sternum for 1 week with no clinical interventions (eg, injection or physical therapy) provided during this period. Patients wore IMUs on their affected arm and sternum for 1 week before TSA with no clinical interventions. The same surgeon then performed TSA via the deltopectoral approach using the same implant system (Bigliani/Flatow Complete Shoulder Solution; Zimmer, Warsaw, IN) for all patients. Patients were discharged home with motion restricted via a sling. Passive ROM under clinician guidance was allowed from discharge to post-TSA week 6, and active assisted ROM was allowed from post-TSA weeks 6 through 9. Once patients were cleared to perform active ROM at 3 months after TSA, clinical ROM metrics and PROMs were captured from patients. Patients then wore the sensors for 6 consecutive weeks. At 1 year after TSA, 1 week of IMU data capture was completed.

Data were processed daily. Shoulder elevation was binned in 0.5-second and 5° increments (0°-5°, 5°-10°, and so on). Average elevation during each time bin was computed, and a corresponding count within each angle bin was incremented. The total count within each angle bin was then converted to the percentage of the day spent in each angle bin. Other IMU-based metrics were daily average and maximum shoulder elevation. Daily metrics were averaged weekly, which were subsequently averaged across subjects.

Appropriate statistical tests were used to compare subject demographic data, IMU-based metrics, PROMs, and goniometric ROM between the cohorts during each week. Specifically, 2-tailed *t* tests were used for continuous variables, 2-tailed *t* tests of proportions were used for non-numeric categorical variables, and 2-tailed Mann-Whitney *U* tests were used for numerical categorical variables. In addition, correlations were conducted comparing demographic data, IMU-based metrics, PROMs, and clinical ROM. The α level was set at .05 for all statistical analyses.

Results

All subjects were well healed at 1 year after TSA as assessed by the operating surgeon, with no revision surgical procedures required. Subject demographic data are contained in Table I. No significant demographic differences were noted between the cohorts. PROMs and clinical ROM are shown in Table II. The PROMIS PCS and MCS scores for controls were greater than both pre- and post-TSA values. The ASES score significantly improved in patients after TSA but was significantly worse than that in control subjects at all times. In contrast, patient pain significantly improved after TSA and was equal to pain in controls. Critically, clinical ROM metrics were well matched with previous studies of healthy individuals[1,4,35] and patients both before and after TSA.[3,38] An interesting finding was that clinical flexion improved significantly after TSA and was equal to that in controls. Clinical external rotation improved similarly after surgery but was always less than that in controls.

Daily average elevation for controls and patients before TSA and after TSA are displayed in Figure 3. Average elevation was not significantly different between the cohorts at any time. Daily maximum elevation for controls and patients before TSA and after TSA are displayed as box-and-whisker plots in Figure 4. Control subject maximum elevation was greater than patient maximum elevation during pre-TSA and post-TSA weeks 1 and 2. However, maximum elevation was equal between the cohorts thereafter.

Binned elevation for movements of less than 90° is displayed in Figure 5, *A*, in 15° bins (0°-15°, 15°-30°, and so on). Prior to TSA, patient performance and control performance were equal, with 96.1% and 96.2% of the day, respectively, spent below 90° of elevation. More specifically, the percentage of the day spent under 30° was 50.2% before TSA and steadily decreased each week after TSA to 42.1% at 1 year after TSA. Binned elevation for movements above 90° of elevation is displayed in Figure 5, *B*, in 45° bins (90°-135° and 135°-180°). As with movements under 90° of elevation, control performance and patient performance before TSA were equal, with 3.9% and 3.8% of the day, respectively, spent over 90°. After surgical intervention, patients reduced the amount of time spent above 90° during the first post-TSA week to 2.4%. However, patients increased the percentage of the day spent above 90° of elevation each week thereafter, with 6.1% above 90° during post-TSA week 6 and 5.0% above 90° during the 1-year follow-up week.

All correlations are contained in Table III. A significant correlation was found between clinical flexion and clinical external rotation. No significant correlations were noted between either clinical ROM metric and any IMU-based metric. Similarly, we found no significant correlations between the PROMIS physical score and any clinical ROM metric or any IMU-based ROM metric. In addition, no significant correlations were noted between the PROMIS mental score and any clinical ROM metric or any IMU-based ROM metric. However, significant correlations were noted between the ASES score and clinical flexion ($\rho = 0.67$, $P = .002$), clinical external rotation ($\rho = 0.78$, $P = .0001$), IMU average elevation ($\rho = 0.53$, $P = .02$), IMU maximum elevation ($\rho = 0.62$, $P = .006$), and IMU percentage above 90° of elevation ($\rho = 0.71$, $P = .0009$).

Discussion

Previous work on shoulder ROM in patients undergoing TSA has centered on data captured in the clinic or laboratory. This type of assessment likely undervalues patients' experience in their home setting. As such, we used a previously validated method[8] to capture similar data in patients both before and after TSA in their daily environments.

Our prospective analysis comparing patients with healthy individuals found no significant difference at any

Table I Subject demographic characteristics and associated *P* values for statistical comparisons between control subjects and patients undergoing TSA

Metric	Control	TSA	*P* value
Subjects, n	10	10	—
Sex, n	4 M and 6 F	6 M and 4 F	.23
Age, yr	69 ± 20	70 ± 8	.92
Handedness (where 1.0 indicates R and −1.0 indicates L)	0.6 ± 0.5	0.2 ± 0.8	.20
Sensor side	9 R and 1 L	7 R and 3 L	.47
Before TSA			
Duration, d	7 ± 0	7 ± 0	>.99
Frequency, h/d	13.5 ± 2.9	12.9 ± 2.5	.64
After TSA			
Duration, d	—	42 ± 0	—
Frequency, h/d	—	10.4 ± 4.1	—
1 yr after TSA			
Duration, d	—	7 ± 0	—
Frequency, h/d	—	9.2 ± 2.6	—

TSA, total shoulder arthroplasty; *M*, male; *F*, female; *R*, right; *L*, left.

Table II Patient-reported outcome measures, clinical goniometric range of motion and associated *P* values

	Control	TSA		*P* Values		
		Before	After	C vs. Pre	C vs. Post	Pre vs. Post
Flexion, °	158±19	97±33	148±25	0.0002*	0.33	0.002*
ER, °	73±20	14±10	40±13	<0.0001*	0.002*	0.0007*
Pain rating	2±1	4.5±1	1±1	0.007*	0.50	0.008*
PCS	57±7	45±10	48±7	0.01*	0.01*	0.50
MCS	57±7	51±4	48±5	0.02*	0.003*	0.18
ASES	92±9	44±16	73±18	<0.0001*	0.007*	0.02*

TSA, total shoulder arthroplasty; *C*, control; *ER*, external rotation; *PROMIS*, Patient-Reported Outcomes Measurement Information System; *PCS*, physical component summary; *MCS*, mental component summary; *ASES*, American Shoulder and Elbow Surgeons; *MAD*, median absolute deviation.
Pain rating is listed as median ± MAD. PROMIS PCS, PROMIS MCS, and ASES scores and clinical range of motion are listed as mean ± standard deviation.
* Significant correlation.

time between the cohorts with respect to IMU-based average elevation. However, a significant correlation was noted between IMU-based average elevation and the ASES score. This was expected though because previous studies have shown the connection between the ASES score and physical function.[41] However, because no differences were found between the cohorts for this metric, we believe that average shoulder elevation is not fruitful for establishing function before or after TSA.

In contrast to average elevation, IMU-based maximum elevation was significantly greater in controls than in patients during the pre-TSA assessment and post-TSA week 1 and week 2 time points. An interesting finding was that patients were equal to controls with respect to IMU-based maximum elevation beyond this time point. This matches clinical information about deficiencies in clinical ROM both before TSA and acutely after TSA.[31] More critically, this confirmed our first hypothesis that patients would have reduced maximum elevation prior to surgical intervention. In addition, we discovered that IMU maximum elevation was strongly correlated with the ASES score. Again, this was anticipated given previous work highlighting the connection between the ASES score and physical function.[41] Given the significant improvement in patient IMU-based maximum elevation and its correlation with the ASES score, we believe that maximum elevation measured by IMUs can be used to assess shoulder function before TSA and during the acute post-TSA recovery phase.

In addition to notable improvements in IMU-based maximum elevation after TSA, we found that patients steadily decreased the amount of time spent under 30° of elevation and correspondingly increased the amount of time spent above 90° of elevation. In other words, after TSA, patients were able to spend more time with their arms above their heads. It is interesting that not only did patients quantitatively improve after surgery but also subjective patient performance improved as measured by the significant correlation between the ASES score and time spent above 90°. Similarly to the correlation between the ASES score and average or maximum elevation, this was expected.[41] Thus, we confirmed our second hypothesis. As a result of the significant increases in time above 90° and corresponding

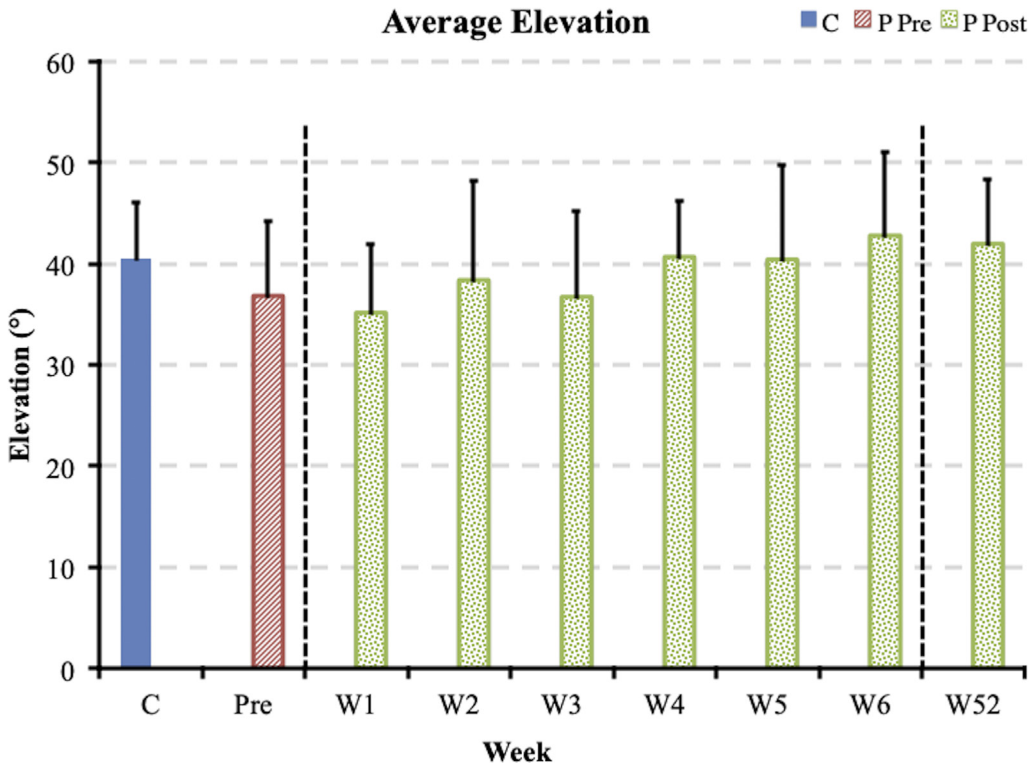

Figure 3 Average shoulder elevation for controls (*C*, *solid bars*) and total shoulder arthroplasty (TSA) patients (before TSA [*P Pre*, *striped bars*] and after TSA [*P Post*, *dotted bars*]). *W*, week.

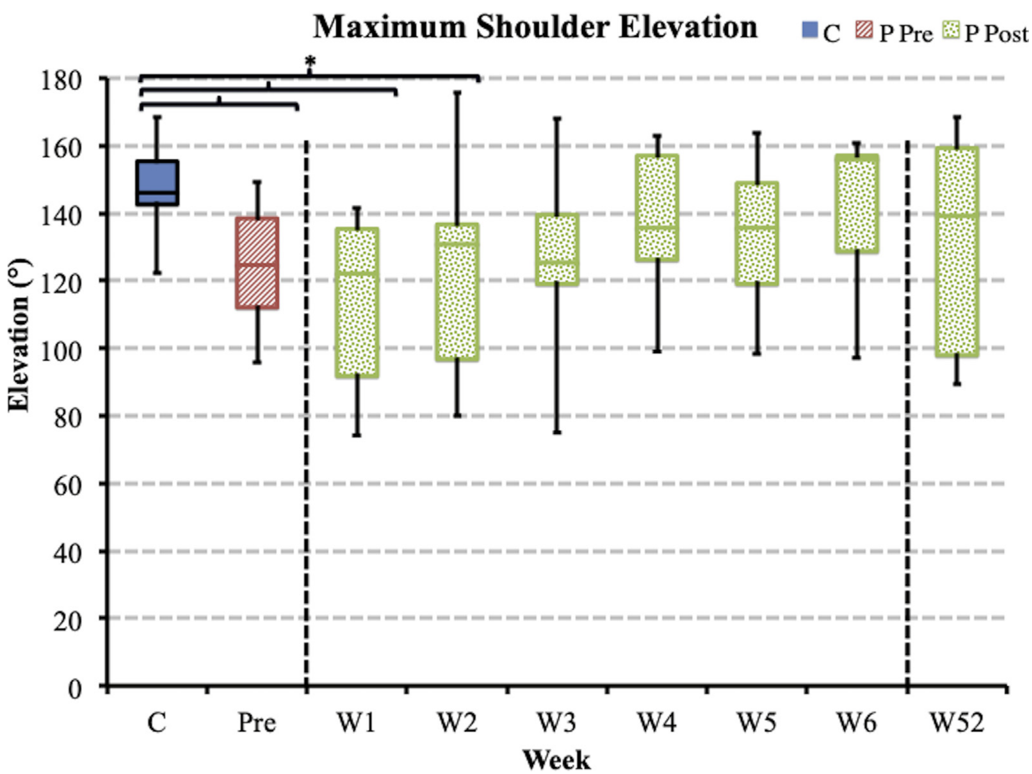

Figure 4 Maximum shoulder elevation for controls (*C*, *solid bars*) and total shoulder arthroplasty (TSA) patients (before TSA [*P Pre*, *striped bars*] and after TSA [*P Post*, *dotted bars*]). Statistically significant differences between the cohorts are denoted by the *asterisk*. *W*, week.

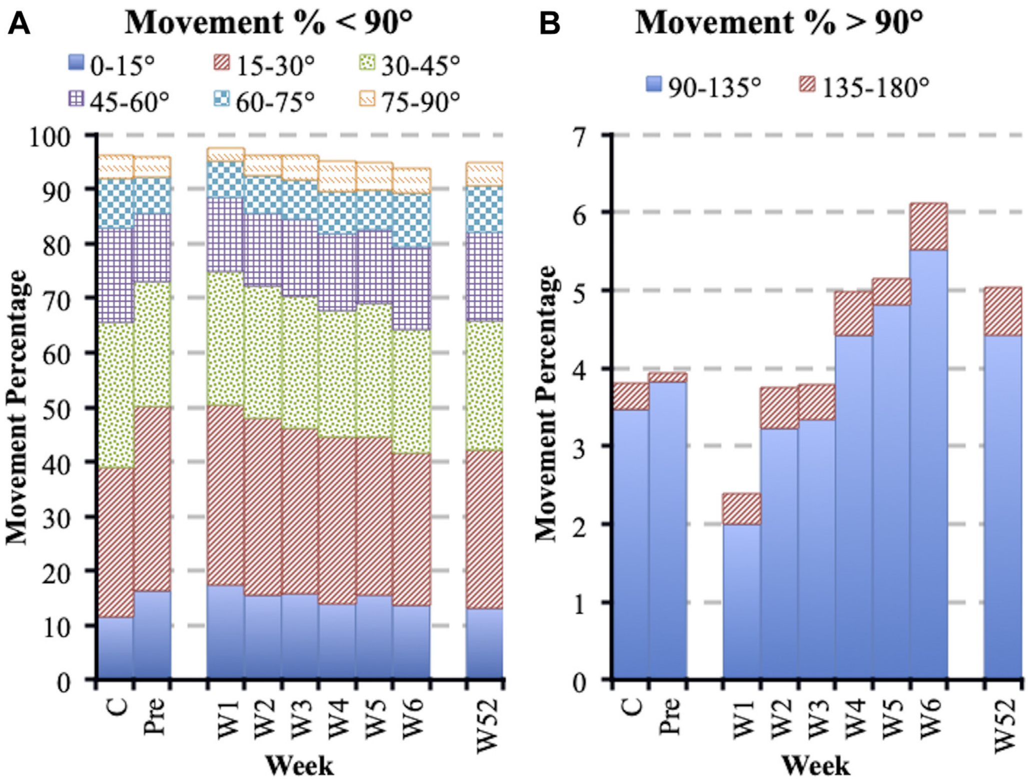

Figure 5 Movement percentage less than 90° of elevation binned in 15° increments (**A**) and greater than 90° of elevation binned in 45° increments (**B**). *W*, week.

Table III Patient Spearman (discrete variables) and Pearson (continuous variables) correlations including comparisons between IMU-based metrics, clinical range of motion, and PROMs

	Flexion	ER	PROMIS PCS score	PROMIS MCS score	ASES score	Pain rating
Flexion						
Correlation coefficient	—	0.77	0.27	−0.04	0.67	−0.47
P value	—	<.0001*	.28	.87	.002*	.05
ER						
Correlation coefficient	—	—	0.42	−0.08	0.78	−0.27
P value	—	—	.08	.77	.0001*	.28
IMU average						
Correlation coefficient	0.23	0.44	0.21	0.45	0.53	−0.33
P value	.37	.07	.40	.06	.02*	.18
IMU maximum						
Correlation coefficient	0.36	0.40	0.06	0.37	0.62	−0.20
P value	.15	.10	.82	.13	.006*	.42
IMU for 0°-30°						
Correlation coefficient	−0.24	−0.34	−0.05	−0.42	−0.38	0.36
P value	.34	.16	.83	.08	.12	.15
IMU for 90°-180°						
Correlation coefficient	0.05	0.44	0.27	0.32	0.71	−0.30
P value	.84	.06	.27	.20	.0009*	.23

IMU, inertial measurement unit; *PROMs*, patient-reported outcome measures; *ER*, external rotation; *PROMIS*, Patient-Reported Outcomes Measurement Information System; *PCS*, physical component summary; *MCS*, mental component summary; *ASES*, American Shoulder and Elbow Surgeons.
* Significant correlation.

decreases in time below 30° and the strong correlation with the ASES score, we think that capturing the amount of time an individual spends above 90° of elevation with IMUs is critical for assessing chronic post-TSA shoulder function. It may seem surprising that TSA patients outperformed control subjects with respect to time spent above 90°. However, despite the small sample size, this was unsurprising for several reasons. First, it is common anecdotally for individuals with newfound motion to repetitively test that ability after intervention for a variety of reasons (eg, pain-free motion or larger ROM). A second possible reason TSA patients outperformed healthy subjects on this metric is the patients' post-TSA rehabilitation requirements. After TSA, patients participate in a variety of rehabilitation activities including outpatient, in-home, and self-guided exercises that require frequent humeral elevation above 90°. In contrast, healthy subjects are not required to do so and as a result perform worse with respect to this metric.

Clinically, we found that both flexion and external rotation improved compared with preoperative values after TSA. However, patient external rotation remained reduced below that of controls, whereas flexion was equal between patients after surgery and controls. We did find a significant correlation between clinical flexion and external rotation. However, this was unsurprising given that the deltoid muscle is in part responsible for both actions[32,39] and could also be dictated by capsular releases performed during surgery. In addition, we found a significant correlation between clinical goniometric flexion and the ASES score. The ASES score has been previously connected to maximum goniometric ROM[19,26,34]; however, we found no connection between goniometric ROM and any IMU-based ROM metric. Although the small sample size of this study may have contributed to this phenomenon, a more likely possibility is that because we allowed patients to move as desired without requirements to maximally elevate their arms, our IMU-based maximum elevation may not represent the patients' full ROM. Rather, IMU-based maximum elevation likely represented maximum self-selected elevation and thus had no connection to clinical goniometric maximum ROM. Given the clear relationships between post-TSA recovery and IMU-based measures discussed previously, we believe that continuously monitoring shoulder elevation using IMUs is a far superior approach for assessing pre- and post-TSA shoulder function than clinically capturing goniometric ROM. Specifically, IMUs offer improved accuracy and continuous measures compared with goniometry. However, we did not require subjects in this study to reach their maximum ROM while wearing the IMUs. As such, goniometric ROM likely represents true maximum ROM while IMU-based maximum ROM represents each patient's self-selected peak ROM. Accordingly, IMU maximum in this effort should be viewed as complementary to goniometric maximum. Future efforts should require patients to reach maximally while donning IMUs to more realistically capture both maximum ROM and ROM use each day.

Additional metrics typically captured clinically that we also collected in our study were the PROMIS physical and mental scores. Previous work has established that PROMIS tests are superior to other PROMs for assessing shoulder function including the ASES score.[2] Despite this fact, control PROMIS physical and mental scores were significantly greater than patient scores before and after TSA. Moreover, we found no correlations between PROMIS scores and any IMU-based ROM metric. These findings indicate that other PROMs (ie, ASES score) are better for subjectively capturing shoulder function than PROMIS-10 physical and mental assessments. However, it should be recognized that the sample size of this study is relatively small for making definitive conclusions about the superiority of specific PROMs in this particular population. Future efforts will require larger sample sizes to make stronger conclusions.

We acknowledge several limitations with our work. First, we were chiefly interested in sagittal shoulder ROM recovery after TSA. This choice was made because we were primarily interested in monitoring how the impacted joint construct functioned after intervention. This choice was warranted given the body of previous work highlighting shoulder elevation as a critical metric for accomplishing upper-extremity ADLs.[4,25] However, this choice neglects other planes of motion, other joints, and hand elevation, all of which are necessary to accomplish upper-extremity activities using varying strategies. In particular, we are currently unable to capture the paradoxical phenomenon wherein less humeral elevation may be needed as external rotation improves. As such, future work should include capture of other planes of motion and other joint kinematics with multiple IMUs attached as a network across multiple segments.

An additional limitation of our study is the discrete set of post-TSA variables we assessed both clinically and via IMUs. Specifically, we noted that maximum elevation recovered acutely (by post-TSA week 2) and time spent above 90° recovered chronically. However, it is possible that there are additional metrics that may be critical for recovery after TSA, including strength and coordination. We also treated all metrics in isolation despite the possibility that multiple metrics in combination better define recovery. For example, an individual achieving higher maximum elevation than another individual but spending equal time above 90° is likely objectively performing better. However, this study did not investigate multifactorial recovery, and no such conclusions can be drawn. Future studies should investigate developing metrics that incorporate multiple potential ROM recovery variables.

Another limitation of this work is our decision to allow patients to move as desired without guidelines from us. Specifically, because we did not tell patients to intentionally move through their entire ROM including high elevations, we do not know whether each patient's daily IMU-based maximum elevation is his or her maximum possible ROM. As a result, in future iterations, it may be useful to instruct patients to reach as high as possible once in the morning and once in the afternoon to ensure that we are capturing not only ROM use but also maximum intentional ROM.

A final limitation of our study is the inability to establish the location of each subject's visual gaze despite the connection many studies have established between upper-extremity performance and visual feedback.[12,13,36] Many individuals accomplish tasks with their upper extremities by elevating their gaze (eg, 45° upward) and matching their hand position to the location of their gaze. As a result, it is often possible to complete many overhead tasks with humeral elevations lower than 90°. As such, future studies should investigate not only additional upper-extremity segments but also the location of an individual's visual arc. This information will more wholly define each patient's upper-extremity task performance.

Conclusion

This study successfully used a validated method for continuously capturing shoulder ROM in patients undergoing TSA while in their own environments. Our results indicate that maximum elevation as captured by IMUs should be used to capture acute shoulder function recovery, time spent above 90° should be leveraged to assess chronic shoulder function recovery, and the ASES score should be used as the preferred PROM adjuvant data point to subjectively evaluate shoulder function. Perhaps more critically, the results establish a recovery curve for well-recovering patients after TSA. The method and results are also a significant improvement on the knowledge base regarding expected biomechanics both before and after shoulder arthroplasty. Using this approach facilitates continuous feedback to clinical teams about the joint health of their patients.

Acknowledgments

The authors are grateful for the efforts of Dan Ressler and Lisa Davis of the Dartmouth-Hitchcock Medical Center, Clinical Research Unit, for patient recruitment.

Disclaimer

Funding for this work was provided by Dr. Van Citters' discretionary funds.

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References

1. Barnes CJ, Van Steyn SJ, Fischer RA. The effects of age, sex, and shoulder dominance on range of motion of the shoulder. J Shoulder Elbow Surg 2001;10:242-6.
2. Beckmann JT, Hung M, Bounsanga J, Wylie JD, Granger EK, Tashjian RZ. Psychometric evaluation of the PROMIS Physical Function Computerized Adaptive Test in comparison to the American Shoulder and Elbow Surgeons score and Simple Shoulder Test in patients with rotator cuff disease. J Shoulder Elbow Surg 2015;24:1961-7. https://doi.org/10.1016/j.jse.2015.06.025
3. Boardman ND III, Cofield RH, Bengtson KA, Little R, Jones MC, Rowland CM. Rehabilitation after total shoulder arthroplasty. J Arthroplasty 2001;16:483-6.
4. Boone D, Azen S. Normal range of motion of joints in male subjects. J Bone Joint Surg Am 1979;61:756-9.
5. Braun S, Millett PJ, Yongpravat C, Pault JD, Anstett T, Torry MR, et al. Biomechanical evaluation of shear force vectors leading to injury of the biceps reflection pulley: a biplane fluoroscopy study on cadaveric shoulders. Am J Sports Med 2010;38:1015-24. https://doi.org/10.1177/0363546509355142
6. Brown DD, Friedman RJ. Postoperative rehabilitation following total shoulder arthroplasty. Orthop Clin North Am 1998;29:535-47.
7. Bryant D, Litchfield R, Sandow M, Gartsman G, Guyatt G, Kirkley A. A comparison of pain, strength, range of motion, and functional outcomes after hemiarthroplasty and total shoulder arthroplasty in patients with osteoarthritis of the shoulder. J Bone Joint Surg Am 2005;87:1947-56. https://doi.org/10.2106/JBJS.D.02854
8. Chapman RM, Torchia MT, Bell JE, Van Citters DW. Assessing shoulder biomechanics of healthy elderly individuals during activities of daily living using inertial measurement units: high maximum elevation is achievable but rarely used. ASME J Biomech Eng 2019;141:041001-7. http://doi.org/10.1115/1.4042433.
9. Department of Research and Scientific Affairs, American Academy of Orthopaedic Surgeons. Annual incidence of common musculoskeletal procedures and treatment. Rosemont, IL: Department of Research and Scientific Affairs, American Academy of Orthopaedic Surgeons; 2018.
10. El-Gohary M, McNames J. Shoulder and elbow joint angle tracking with inertial sensors. IEEE Trans Biomed Eng 2012;59:2635-41. https://doi.org/10.1109/TBME.2012.2208750
11. Fisher ES, Bell JE, Tomek IM, Esty AR, Goodman DC. Trends and regional variation in hip, knee, and shoulder replacement. A Dartmouth Atlas surgery report. Lebanon, NH: Dartmouth Atlas Project; 2010. p. 1-24.
12. Ghez C, Gordon J, Ghilardi M. Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy. J Neurophysiol 1995;73:361-72.
13. Gonzalez-Alvarez C, Subramanian A, Pardhan S. Reaching and grasping with restricted peripheral vision. Ophthalmic Physiol Opt 2007;27:265-74. https://doi.org/10.1111/j.1475-1313.2006.00476.x
14. Gore DR, Murray MP, Sepic SB, Gardner GM. Shoulder-muscle strength and range of motion following surgical repair of full-thickness rotator-cuff tears. J Bone Joint Surg Am 1986;68:266-72.
15. Hassan EA, Jenkyn TR, Dunning CE. Direct comparison of kinematic data collected using an electromagnetic tracking system versus a digital optical system. J Biomech 2007;40:930-5. https://doi.org/10.1016/j.jbiomech.2006.03.019
16. Hawkins R, Bell R, Jallay B. Total shoulder arthroplasty. Clin Orthop Relat Res 1989;242:188-94.
17. Hung M, Baumhauer JF, Latt LD, Saltzman CL, SooHoo NF, Hunt KJ, et al. Validation of PROMIS Physical Function computerized adaptive tests for orthopaedic foot and ankle outcome research. Clin Orthop Relat Res 2013;471:3466-74. https://doi.org/10.1007/s11999-013-3097-1
18. HW Healthcare Advisors. Medicare Part B therapy services fee schedule—certain outpatient rehabilitation CPT and HCPCS codes; 2019.

https://www.hwco.com/wp-content/uploads/2018/06/Therapy-Ohio-2018-Updated-for-SUSTAIN-Care-Act-of-2018.pdf. Accessed 19 Dec 2018.

19. Iannotti JP, Norris TR. Influence of preoperative factors on outcome of shoulder arthroplasty for glenohumeral osteoarthritis. J Bone Joint Surg Am 2003;85:251-8.
20. Ide J, Takagi K. Early and long-term results of arthroscopic treatment for shoulder stiffness. J Shoulder Elbow Surg 2004;13:174-9. https://doi.org/10.1016/j.jse.2003.11.001
21. Ilfeld BM, Wright TW, Enneking FK, Morey TE. Joint range of motion after total shoulder arthroplasty with and without a continuous interscalene nerve block: a retrospective, case-control study. Reg Anesth Pain Med 2005;30:429-33. https://doi.org/10.1016/j.rapm.2005.06.003
22. Jackson M, Michaud B, Tetreault P, Begon M. Improvements in measuring shoulder joint kinematics. J Biomech 2012;45:2180-3. https://doi.org/10.1016/j.jbiomech.2012.05.042
23. Kasten P, Maier M, Wendy P, Rettig O, Raiss P, Wolf S, et al. Can shoulder arthroplasty restore the range of motion in activities of daily living? A prospective 3D video motion analysis study. J Shoulder Elbow Surg 2010;19:59-65. https://doi.org/10.1016/j.jse.2009.10.012
24. Luinge HJ, Veltink PH, Baten CT. Ambulatory measurement of arm orientation. J Biomech 2007;40:78-85. https://doi.org/10.1016/j.jbiomech.2005.11.011
25. Magermans DJ, Chadwick EK, Veeger HE, van der Helm FC. Requirements for upper extremity motions during activities of daily living. Clin Biomech (Bristol, Avon) 2005;20:591-9. https://doi.org/10.1016/j.clinbiomech.2005.02.006
26. Michener LA, McClure PW, Sennett BJ. American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form, patient self-report section: reliability, validity, and responsiveness. J Shoulder Elbow Surg 2002;11:587-94. https://doi.org/10.1067/mse.2002.127096
27. Norris TR, Iannotti JP. Functional outcome after shoulder arthroplasty for primary osteoarthritis: a multicenter study. J Shoulder Elbow Surg 2002;11:130-5. https://doi.org/10.1067/mse.2002.121146
28. Oldfield RC. The assessment and analysis of handedness: The Edinburgh Inventory. Neuropsychologia 1971;9:97-113.
29. Pro Performance Physical Therapy. PT Fee Schedule. http://properformancetherapy.com/wp-content/uploads/2015/05/Fees.pdf. Accessed 13 Dec 2018.
30. Puskas B, Harreld K, Clark R, Downes K, Virani NA, Frankle M. Isometric strength, range of motion, and impairment before and after total and reverse shoulder arthroplasty. J Shoulder Elbow Surg 2013;22:869-76. https://doi.org/10.1016/j.jse.2012.09.004
31. Raiss P, Bruckner T, Rickert M, Walch G. Longitudinal observational study of total shoulder replacements with cement: fifteen to twenty-year follow-up. J Bone Joint Surg Am 2014;96:198-205. https://doi.org/10.2106/JBJS.M.00079
32. Reinold MM, Wilk KE, Fleisig GS, Zheng N, Barrentine SW, Chmielewski T, et al. Electromyographic analysis of the rotator cuff and deltoid musculature during common shoulder external rotation exercises. J Orthop Sports Phys Ther 2004;34:385-94. https://doi.org/10.2519/jospt.2004.34.7.385
33. Riddle DL, Rothstein JM, Lamb RL. Goniometric reliability in a clinical setting: shoulder measurements. Phys Ther 1986;67:668-73.
34. Roach KE, Budiman-Mak E, Songsiridej N, Lertratanakul Y. Development of a shoulder pain and disability index. Arthritis Care Res 1991;4:143-9.
35. Roy JS, Macdermid JC, Boyd KU, Faber KJ, Drosdowech D, Athwal GS. Rotational strength, range of motion, and function in people with unaffected shoulders from various stages of life. Sports Med Arthrosc Rehabil Ther Technol 2009;1:4. https://doi.org/10.1186/1758-2555-1-4
36. Sergio L, Scott S. Hand and joint paths during reaching movements with and without vision. Exp Brain Res 1998;122:157-64.
37. Sirveaux F, Favard L, Oudet D, Huquet D, Walch G, Molé D. Grammont inverted total shoulder arthroplasty in the treatment of glenohumeral osteoarthritis with massive rupture of the cuff. Results of a multicentre study of 80 shoulders. J Bone Joint Surg Br 2004;86:388-95. https://doi.org/10.1302/0301-620X.86B3
38. Sperling JW, Cofield RH, Schleck CD, Harmsen WS. Total shoulder arthroplasty versus hemiarthroplasty for rheumatoid arthritis of the shoulder: results of 303 consecutive cases. J Shoulder Elbow Surg 2007;16:683-90. https://doi.org/10.1016/j.jse.2007.02.135
39. Wattanaprakornkul D, Halaki M, Boettcher C, Cathers I, Ginn KA. A comprehensive analysis of muscle recruitment patterns during shoulder flexion: an electromyographic study. Clin Anat 2011;24:619-26. https://doi.org/10.1002/ca.21123
40. Windolf M, Gotzen N, Morlock M. Systematic accuracy and precision analysis of video motion capturing systems—exemplified on the Vicon-460 system. J Biomech 2008;41:2776-80. https://doi.org/10.1016/j.jbiomech.2008.06.024
41. Wylie JD, Beckmann JT, Granger E, Tashjian RZ. Functional outcomes assessment in shoulder surgery. World J Orthop 2014;5:623-33. https://doi.org/10.5312/wjo.v5.i5.623