



Functional workspace and patient-reported outcomes improve after reverse and total shoulder arthroplasty

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Background: Low-cost motion analysis systems (LCMASs) have emerged as easy and practical methods to measure the functional workspace (FWS). Thus, we ventured to apply an LCMAS, the Kinect2 gaming camera, to evaluate the FWS in patients with shoulder osteoarthritis (OA) and patients who underwent total shoulder arthroplasty (TSA) or reverse total shoulder arthroplasty (RTSA).

Methods: A cross-sectional study of participants with OA (n = 53), TSA (n = 70), and RTSA (n = 34) was performed. The FWS as measured by an LCMAS, the American Shoulder and Elbow Surgeons (ASES) Standardized Shoulder Assessment Form score, and the Patient-Reported Outcomes Measurement Information System (PROMIS) score were collected. For participants who underwent TSA or RTSA, the FWS was evaluated at 6, 12, and 24 months postoperatively. The correlation of the FWS with the ASES score and PROMIS score was determined. Significance was set at $P < .05$.

Results: Patients who underwent TSA or RTSA had a significantly higher FWS than patients with shoulder OA at almost all time points. Patients who underwent TSA had a significantly higher FWS than patients who underwent RTSA at 24 months after surgery. PROMIS and ASES scores showed strong correlations with the FWS in patients who underwent TSA ($R = 0.75$ [$P < .001$] and $R = 0.83$ [$P < .001$], respectively) and RTSA ($R = 0.84$ [$P < .001$] and $R = 0.73$ [$P < .001$], respectively).

Conclusion: The FWS measured by an LCMAS is an easy and low-cost method to quantify the reachable space of the hand in patients and shows strong correlations with patient-reported outcome measures. This may be a useful tool to assess upper-extremity range of motion before and after shoulder arthroplasty.

Level of evidence: Level III; Case-Control Design; Treatment Study

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Keywords: Shoulder osteoarthritis; total shoulder arthroplasty; reverse total shoulder arthroplasty; functional workspace; Kinect; PROMIS

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Arthritis and musculoskeletal conditions are among the most widespread diseases in America, affecting 1 in 3 adults.¹⁵ Shoulder osteoarthritis (OA) is a debilitating disorder correlated with limited functional capacity and poor quality-of-life scores. Presently, there are no known interventions that alter the natural course of early OA, and current treatments aim to minimize pain and maximize function, often with joint replacement.¹⁵

For patients with severe shoulder OA, shoulder replacement surgical procedures including total shoulder arthroplasty (TSA) and reverse total shoulder arthroplasty (RTSA) are reliable treatment options that improve patient-reported pain, function, and quality of life.²⁰ To assess these operative interventions, clinical tools including patient-reported outcome (PRO) scores and evaluation of shoulder motion are used.

PRO scores offer qualitative assessments that are designed to improve patient-centered care by giving patients the opportunity to express their health status.¹⁶ The National Institutes of Health started the Patient-Reported Outcomes Measurement Information System (PROMIS) initiative to establish a national standard for the measure of these PRO scores. The PROMIS Physical Function Upper Extremity score has been used to assess patient status in shoulder diseases such as shoulder OA and rotator cuff tears.^{17,19} In addition, the American Shoulder and Elbow Surgeons (ASES) Standardized Shoulder Assessment Form is an evaluative and discriminative instrument for patients with shoulder dysfunction. It has been shown to be reliable, valid, and responsive to clinical change, corroborating its use to assess functional limitations.¹⁴

Clinical evaluation of motion of the shoulder is challenging because of its complex anatomy and range of motion. For evaluation of shoulder motion in clinical settings, trained clinicians often use observational scores or perform goniometric measurements. However, these measures are restricted by their subjectivity, reproducibility, and user dependency.⁹ The functional workspace (FWS) of the upper extremity has been defined as all points in space where the hand can touch relative to the shoulder joint.⁷ The current gold standard to measure dynamic upper-extremity motion uses 3-dimensional (3D) motion capture technology, which incorporates multiple high-resolution cameras to track body movements.^{18,22} Such techniques may readily measure upper-extremity motion and quantify the FWS but are limited in practical clinical application because of high costs, space, time, and labor requirements.²²

Low-cost motion analysis systems (LCMASs) are inexpensive, accurate, easy-to-use, time-efficient methods to measure upper-extremity motion in a clinical setting.²² The Microsoft Kinect2 system (Redmond, WA, USA) is a commercially available LCMAS that uses an infrared depth camera to detect human body position using proprietary surface mapping technology. The use of the Microsoft Kinect camera in the measurement of shoulder positions has been extensively validated by comparison

with traditional multiplanar motion analysis systems.^{4,12,13,25} Assessment of the validity and reproducibility of the Kinect system to measure the upper-extremity FWS has also been performed.^{1,8,24} To date, there have been studies applying the depth camera-measured FWS to patient populations with neuromuscular conditions or adhesive capsulitis, as well as patients undergoing rehabilitation.^{3,10,11} Across these groups, depth cameras showed promise in establishing diagnoses and distinguishing individuals even with varying degrees of upper-limb impairment. However, application of this technology to degenerative conditions such as OA and to patients who have undergone operative treatments has not been explored. In addition, the FWS has not been compared with qualitative assessments such as PROMIS and ASES scores.

In this study, we evaluated the correlation of the FWS with PROMIS and ASES scores in patients with OA, TSA, and RTSA. In addition, we compared the FWS in patients with shoulder OA and patients who have undergone surgery for shoulder OA with either TSA or RTSA as a treatment option after specific time intervals. We hypothesized that the FWS would have moderate to strong correlations with PROMIS and ASES scores across all patient cohorts. We also hypothesized that the FWS would be significantly greater in patients who have undergone TSA or RTSA compared with that in patients with OA.

Materials and methods

We enrolled a convenience sample of 157 patients presenting for either preoperative evaluation for glenohumeral arthritis ($n = 53$) or routine postoperative follow-up after TSA ($n = 70$) or RTSA ($n = 34$) at the University of California, San Francisco Mission Bay Orthopaedic Institute of Sports Medicine in this study. After informed consent was provided, standard demographic data including age, sex, body mass index, surgical treatment, and time since surgery were recorded in a privacy-protected electronic database (Research Electronic Data Capture [REDCap] system). Participants completed the ASES Standardized Shoulder Assessment Form and PROMIS Physical Function Upper Extremity survey in REDCap.

The Kinect2 LCMAS was used to capture participant motion. The camera was positioned 1.5 m above the ground and 2.5 m from the participant. The participant was instructed to perform a series of standardized motions to map the estimated outer and inner volume of points in space that his or her upper extremity could reach. These motions—including elevation of the arm from 0°, 45°, 90°, and 135° relative to the coronal plane, as well as maximal abduction to maximal adduction at the level of the head, chest, abdomen, and waist (Video 1)—simulated activities of daily living (touch top of head, touch mouth, touch contralateral shoulder, touch contralateral hip). The average total time taken to complete these movements was 55 seconds for each arm.

The Kinect system projects infrared light onto the surface of the room and person facing the camera. Using a proprietary algorithm, the camera identifies normal human morphology and determines estimated joint center locations. The estimated joint

center location raw data were collected at 30 Hz using custom software and analyzed with custom MATLAB software (The MathWorks, Natick, MA, USA). Data were filtered with a low-pass Butterworth filter. The motion data were used to generate a point cloud of the motion path of the hand relative to the shoulder. Custom MATLAB software was then used to generate the 3D shell enveloping these data points using Delaunay triangulation² (Fig. 1). The volume of the points within the shell was interpolated to calculate the FWS. The FWS for each participant was normalized by arm length for comparison. In addition, patients were able to instantly visualize their FWS as a 3D volumetric sphere and receive feedback on the examination room laptop after they completed their assigned motions.

All statistics were completed using JMP statistical software (version 14; SAS Institute, Cary, NC, USA). A cross-sectional study of participants with OA ($n = 53$), TSA ($n = 70$), and RTSA ($n = 34$) was performed. One-way analysis of variance and the paired Student t test were used to compare the FWS of patients with OA with the FWS of patients who had undergone TSA or RTSA at 6-, 12-, and 24-month time points, with significance set at $P < .05$.

For comparative analysis of the FWS, ASES score, and PROMIS score, a regression analysis of the FWS, ASES score, and PROMIS score was performed for patients with OA, TSA, and RTSA. Correlation coefficients (R) of 0.30 or less were considered weak; between 0.31 and 0.39, moderate-weak; between 0.40 and 0.60, moderate; between 0.61 and 0.69, moderate-strong; and 0.70 or greater, strong—with significance set at $P < .05$.¹⁶

Results

The mean age was 73.2 years in OA patients, 67.7 years in TSA patients, and 70.4 years in RTSA patients. Regarding sex, 38% of OA, 33% of TSA, and 60% of RTSA patients were female patients. The average length of follow-up after TSA and RTSA surgery was 34.0 months (range, 3-56.8 months) and 28.26 months (range, 3-90.2 months), respectively.

The correlation of the FWS with the PROMIS score yielded a moderate-strong correlation ($R = 0.63$, $P < .001$)

in the combined cohort of all participants. Patients were then categorized into specific cohorts to further demarcate the effect of degenerative disease and operative treatment and its influence on correlation.¹⁵ The PROMIS score showed a weak correlation for patients with OA ($R = 0.24$, $P < .05$). For TSA and RTSA patients, there were strong correlations with their respective PROMIS scores ($R = 0.75$ [$P < .001$] and $R = 0.84$ [$P < .001$], respectively) (Figs. 2 and 3).

The overall correlation of the FWS with the ASES score in the combined cohort of all participants yielded a strong correlation ($R = 0.77$, $P < .001$) (Fig. 4). When the patient groups were separated, the FWS showed a moderate-weak correlation in patients with OA ($R = 0.39$, $P < .05$). For TSA and RTSA patients, the FWS showed strong correlations with the ASES score ($R = 0.83$ [$P < .001$] and $R = 0.73$ [$P < .001$], respectively).

The FWS was significantly greater in TSA patients ($2.21 \pm 0.547 \text{ m}^3$) than RTSA patients ($1.97 \pm 0.499 \text{ m}^3$) and OA patients ($1.61 \pm 0.602 \text{ m}^3$), with $P < .05$ and $P < .001$, respectively. The FWS was significantly greater in RTSA participants than OA participants ($P < .05$).

When postsurgical follow-up intervals within the TSA and RTSA populations were evaluated, patients with OA without operative treatment had a significantly lower FWS (1.61 m^3) than postoperative patients who underwent TSA 6 months prior ($2.03 \pm 0.452 \text{ m}^3$), 12 months prior ($2.35 \pm 0.636 \text{ m}^3$), and 24 months prior ($2.40 \pm 0.508 \text{ m}^3$), with $P < .05$, $P < .001$, and $P < .001$, respectively. Furthermore, patients with OA had a significantly lower FWS (1.61 m^3) than postoperative patients who underwent RTSA 6 months prior ($2.33 \pm 0.405 \text{ m}^3$) and 12 months prior ($2.05 \pm 0.384 \text{ m}^3$), with $P < .05$ and $P < .05$, respectively. The mean FWS of patients with OA was not significantly lower than that of patients who underwent RTSA 24 months prior (1.61 m^3 vs. $1.85 \pm 0.703 \text{ m}^3$), with $P = .334$ (Table I).

In the comparison of the FWS in postoperative patients who underwent TSA or RTSA 6, 12, and 24 months prior,

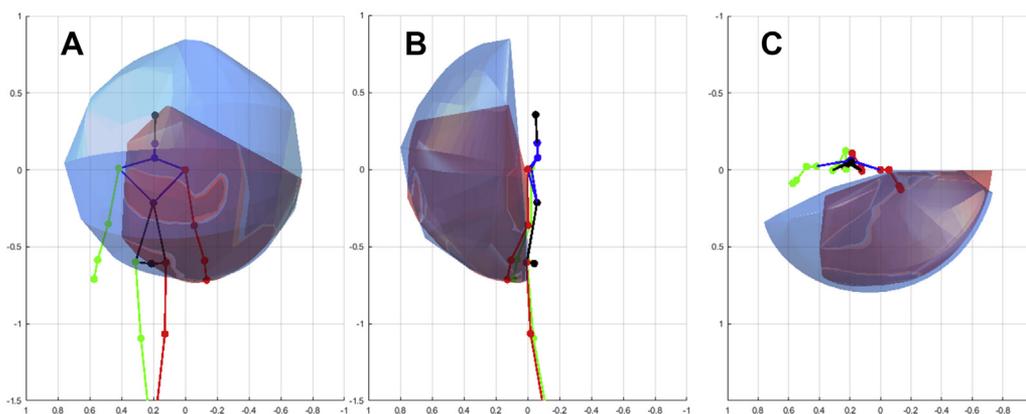


Figure 1 Frontal (A), lateral (B), and axial (C) views of functional workspace for total shoulder arthroplasty (blue cloud) and osteoarthritis (red cloud) participants.

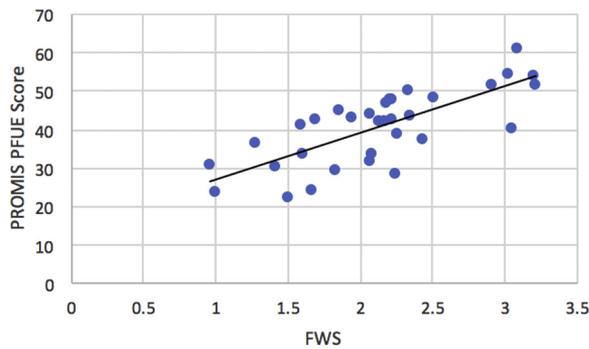


Figure 2 Comparison of functional workspace (*FWS*) in patients after total shoulder arthroplasty and Patient-Reported Outcomes Measurement Information System Physical Function Upper Extremity (*PROMIS PFUE*) score ($R = 0.75$).

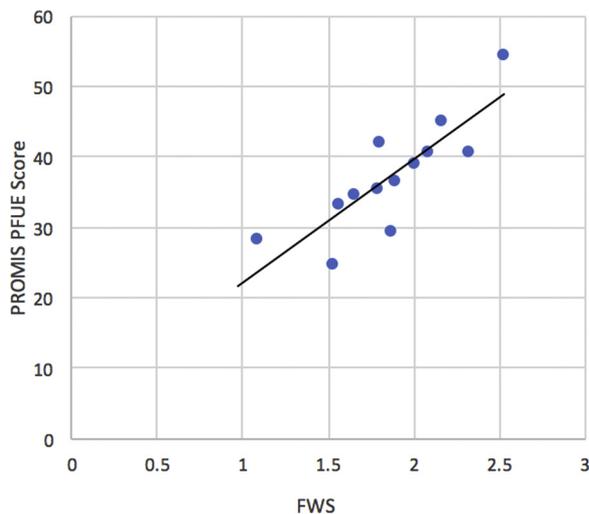


Figure 3 Comparison of functional workspace (*FWS*) of patients after reverse total shoulder arthroplasty and Patient-Reported Outcomes Measurement Information System Physical Function Upper Extremity (*PROMIS PFUE*) score ($R = 0.84$).

those who underwent TSA began to have a significantly higher FWS at 12 months (2.35 m^3) and 24 months (2.40 m^3) postoperatively than that of patients who underwent RTSA 24 months prior (1.85 m^3), with $P < .05$ and $P < .05$, respectively (Fig. 5).

Discussion

The ability to measure and evaluate upper-extremity movements with a portable and inexpensive markerless motion analysis system yields tremendous potential research and clinical applications. As a low-cost motion analysis instrument, the Kinect2 generates a depth image by identifying a pattern of infrared waves emitted by its projector; this depth image is then analyzed to provide coordinates of predetermined body segments without the

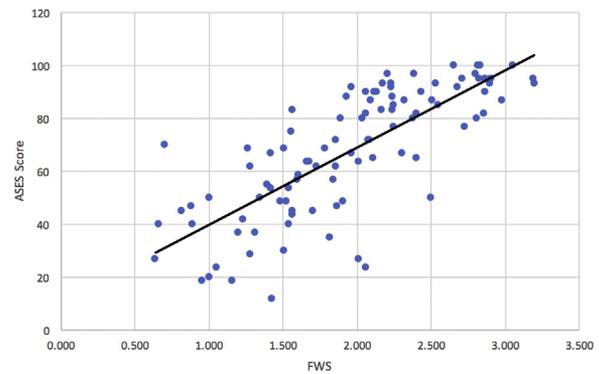


Figure 4 Comparison of functional workspace (*FWS*) of all patients with American Shoulder and Elbow Surgeons (*ASES*) Standardized Shoulder Assessment Form score ($R = 0.77$).

attachment of markers or sensors and without any physical contact with the participant.¹⁰ By offering a volumetric measurement of the range of motion of the upper extremity, it can help assess and improve the functional status of patients seeking treatment for shoulder conditions.⁵

The depth camera-measured FWS was easily procured in the clinic, and the measurement system was portable, capable of being shifted from 1 clinical examination room to another. Studies took less than 4 minutes and could incorporate functional range of motion as well as FWS measurements. Furthermore, patients were able to visualize their FWS on the computer after performing the shoulder movements. On a repeated visit, they were able to visualize a side-by-side comparison of their FWS before and after operative treatment and learn which area had the most room for improvement.

This is the first study correlating the quantitative assessment, FWS, to qualitative measures, such as PROMIS and ASES scores. In our analysis, the results demonstrate that the FWS has a strong correlation with both PROMIS and ASES scores for patients undergoing TSA or RTSA. Furthermore, PROMIS scores have been shown to have a strong correlation with ASES scores and widely accepted PROs such as the Simple Shoulder Test.^{16,17,19} Thus, these results substantiate that the FWS can be an accurate and visual supplement to measuring functional outcome in patients who have undergone these operative treatments. It should be noted that a study has indicated that improvements in range of motion follow the same trend as clinically significant improvements in PROs up to 1 year postoperatively.²⁰ In patients with OA, a weak correlation with both PROMIS and ASES scores was obtained. This could be because of the heterogeneity of the OA population sample, as well as the multifaceted nature of preoperative physical function and the associated PRO scores.²³

When we performed comparison of the FWS of TSA and RTSA patients as separate cohorts, TSA patients had a larger FWS than RTSA patients, suggesting that TSA may produce better functional movement than RTSA in patients

Table I FWS, PROMIS scores, and ASES scores for OA, TSA, and RTSA patients

Assessment	OA preop	TSA			RTSA		
		6 mo postop	12 mo postop	24 mo postop	6 mo postop	12 mo postop	24 mo postop
FWS, m ³ /m	1.61 ± 0.60	2.03 ± 0.45	2.35 ± 0.64	2.40 ± 0.51	2.33 ± 0.41	2.05 ± 0.38	1.85 ± 0.70
ASES Standardized Shoulder Assessment Form score	43.3 ± 16.7	79.4 ± 17.3			79.8 ± 14.8		
PROMIS PFUE score	33.0 ± 5.84	40.72 ± 3.00			37.25 ± 2.72		

FWS, functional workspace; PROMIS, Patient-Reported Outcomes Measurement Information System; ASES, American Shoulder and Elbow Surgeons; OA, osteoarthritis; TSA, total shoulder arthroplasty; RTSA, reverse total shoulder arthroplasty; preop, preoperatively; postop, postoperatively; PFUE, Physical Function Upper Extremity.

Data are presented as mean ± standard deviation.

The ASES and PROMIS scores are the mean values across all postsop time points.

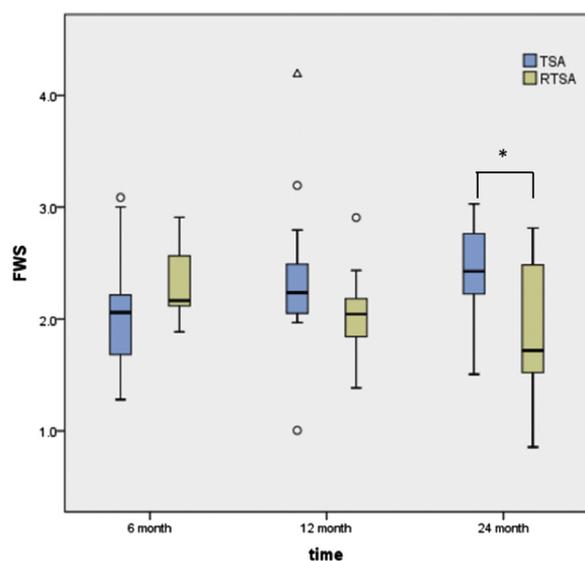


Figure 5 Box plot comparing functional workspace (FWS) of patients 6, 12, and 24 months after total shoulder arthroplasty (TSA) or reverse total shoulder arthroplasty (RTSA). A significant difference ($P < .05$) was shown at 24 months (*). ○ and △ indicate outliers.

with shoulder OA. This increased FWS for TSA is consistent with the general impression that patients who undergo TSA more commonly achieve improved range of motion compared with patients who undergo RTSA.²¹ In addition, another study reported that patients with OA and an intact rotator cuff achieve the best results with TSA.⁵ Nevertheless, this is a cross-sectional study with varying degrees of OA in the population; thus, patients who underwent TSA may previously have had better functional mobility than patients who underwent RTSA, which is often indicated for patients with OA in the setting of rotator cuff deficiency.⁶ Future investigations will conduct a longitudinal study comparing the FWS in patients with OA before and after operative treatment.

When assessed at specific time intervals, the FWS for TSA increased at each postoperative time interval, that is, 6, 12, and 24 months, demonstrating that the FWS increases as time after surgery increases. These results are consistent

with those of studies demonstrating that the majority of improvement is achieved in the first 6 months whereas full improvement is expected by 24 months.^{20,21} For RTSA, there was a decrease in the FWS between 6 and 12 months. There was also a decrease at 24 months, but it was not statistically significant. Because the deltoid substitutes for the nonfunctioning rotator cuff, which is a consequence of RTSA, a decline in the FWS seen between 6 and 12 months could indicate deltoid fatigue over time.¹¹ Alternatively, this cohort was relatively small and may represent the fact that the study was not powered to detect differences in the FWS at different time points.

The limitations of our study include its cross-sectional nature and non-age- and sex-matched demographic characteristics. The patients sampled were a convenience sample of either those presenting for evaluation or those returning for routine postoperative follow-up. Although the procedures were standardized, heterogeneity remains within these nonmatched cohorts at variable follow-up time points. In addition, because the Kinect captures frontal body motion, if a participant rotated his or her hips while performing the shoulder movements, the FWS could have been falsely increased as the participant could have abducted more and increased the volumetric space that his or her hand reached. If a participant was wearing a loose-fitting shirt or jacket, the loose ends of the garment were taped together to make it skintight. Nevertheless, it was possible that the tape slacked during active range of motion, which may have altered the estimated joint location. Finally, this study was administered at a single academic institution; therefore, our results may not apply to all patient populations or locations.

Conclusion

The depth camera used in the Kinect2 LCMAS was a safe, time-efficient, and easy-to-use tool to assess a clinically meaningful measurement of the FWS in patients after TSA or RTSA and in patients with OA. This study also demonstrated a strong correlation between the

FWS and the PROMIS and ASES scores, suggesting that there is considerable clinical validity to the tool. Because the FWS can provide real-time visual feedback in the clinic, it may be a useful tool to assist patients and providers in assessing the upper-extremity FWS in patients with shoulder pathology and before and after shoulder arthroplasty.

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Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jse.2019.03.029>.

References

- Clement J, Raison M, Rouleau DM. Reproducibility analysis of upper limbs reachable workspace, and effects of acquisition protocol, sex and hand dominance. *J Biomech* 2018;68:58-64. <https://doi.org/10.1016/j.jbiomech.2017.12.010>
- Curran PF, Bagley AM, Sison-Williamson M, James MA. Three-dimensional functional workspace of thumb prehension. *Clinical Biomechanics (Bristol, Avon)* 2019;63:63-72. <https://doi.org/10.1016/j.clinbiomech.2019.02.017>
- de Bie E, Oskarsson B, Joyce NC, Nicorici A, Kurillo G, Han JJ. Longitudinal evaluation of upper extremity reachable workspace in ALS by Kinect sensor. *Amyotroph Lateral Scler Frontotemporal Degener* 2017;18:17-23. <https://doi.org/10.1080/21678421.2016.1241278>
- Huber ME, Seitz AL, Leeser M, Sternad D. Validity and reliability of Kinect skeleton for measuring shoulder joint angles: a feasibility study. *Physiotherapy* 2015;101:389-93. <https://doi.org/10.1016/j.physio.2015.02.002>
- Johnson C, Johnson DJ, Liu JN, Dines JS, Dines DM, Gulotta LV, et al. Return to sports after shoulder arthroplasty. *World J Orthop* 2016;7:519-26. <https://doi.org/10.5312/wjo.v7.i9.519>
- Kiet TK, Feeley BT, Naimark M, Gajju T, Hall SL, Chung TT, et al. Outcomes after shoulder replacement: comparison between reverse and anatomic total shoulder arthroplasty. *J Shoulder Elbow Surg* 2015;24:179-85. <https://doi.org/10.1016/j.jse.2014.06.039>
- Klopčar N, Tomsic M, Lenarcic J. A kinematic model of the shoulder complex to evaluate the arm-reachable workspace. *J Biomech* 2007;40:86-91. <https://doi.org/10.1016/j.jbiomech.2005.11.010>
- Kurillo G, Chen A, Bacjcsy R, Han J. Evaluation of upper extremity reachable workspace using Kinect camera. *Technol Health Care* 2013;21:641-56. <https://doi.org/10.3233/THC-130764>
- Kurillo G, Han JJ, Obdrzalek S, Yan P, Abresch RT, Nicorici A, et al. Upper extremity reachable workspace evaluation with Kinect. *Technol Health Care* 2013;184:247-53. <https://doi.org/10.3233/978-1-61499-209-7-247>
- Lee SH, Yoon C, Chung SG, Kim HC, Kwak Y, Park HW, et al. Measurement of shoulder range of motion in patients with adhesive capsulitis using a Kinect. *PLoS One* 2015;10:e0129398. <https://doi.org/10.1371/journal.pone.0129398>
- Liu JN, Garcia GH, Mahony G, Wu HH, Dines DM, Warren RF, et al. Sports after shoulder arthroplasty: a comparative analysis of hemiarthroplasty and reverse total shoulder replacement. *J Shoulder Elbow Surg* 2016;25:920-6. <https://doi.org/10.1016/j.jse.2015.11.003>
- Matsen FA 3rd, Lauder A, Keeling P, Cheronas AL. Measurement of active shoulder motion using the Kinect, a commercially available infrared position detection system. *J Shoulder Elbow Surg* 2016;25:216-23. <https://doi.org/10.1016/j.jse.2015.07.011>
- Matthew RP, Seko S, Bacjcsy R, Lotz J. Kinematic and Kinect validation of an improved depth camera motion assessment system using rigid bodies. *IEEE J Biomed Health Inform* 2019;23:1784-93. <https://doi.org/10.1109/JBHI.2018.2872834>
- Michener L, McClure P, Sennett B. 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>
- Milllett PJ, Gobezie R, Boykin RE. Shoulder osteoarthritis: diagnosis and management. *Am Fam Physician* 2008;78:605-11. <https://doi.org/10.1177/1758573216644183>
- Minoughan CE, Schumaier AP, Fritch JL, Grawe BM. Correlation of Patient-Reported Outcome Measurement Information System Physical Function Upper Extremity Computer Adaptive Testing, with the American Shoulder and Elbow Surgeons Shoulder Assessment Form and Simple Shoulder Test in patients with shoulder pain. *Arthroscopy* 2018;34:1430-6. <https://doi.org/10.1016/j.arthro.2017.11.040>
- Minoughan CE, Schumaier AP, Fritch JL, Grawe BM. Correlation of PROMIS Physical Function Upper Extremity Computer Adaptive Test with American Shoulder and Elbow Surgeons shoulder assessment form and Simple Shoulder Test in patients with shoulder arthritis. *J Shoulder Elbow Surg* 2018;27:585-91. <https://doi.org/10.1016/j.jse.2017.10.036>
- Parel I, Jaspers E, De Baets L, Amoresano A, Cutti AG. Motion analysis of the shoulder in adults: kinematics and electromyography for the clinical practice. *Eur J Phys Rehabil Med* 2016;52:575-82.
- Patterson BM, Orvets ND, Aleem AW, Keener JD, Calfee RP, Nixon DC, et al. Correlation of Patient-Reported Outcomes Measurement Information System (PROMIS) scores with legacy patient-reported outcome scores in patients undergoing rotator cuff repair. *J Shoulder Elbow Surg* 2018;27(Suppl):S17-23. <https://doi.org/10.1016/j.jse.2018.03.023>
- Puzzitiello RN, Agarwalla A, Liu JN, Cvetanovich GL, Romeo AA, Forsythe B, et al. Establishing maximal medical improvement after anatomic total shoulder arthroplasty. *J Shoulder Elbow Surg* 2018;27:1711-20. <https://doi.org/10.1016/j.jse.2018.03.007>
- Simovitch R, Flurin PH, Marczuk Y, Friedman R, Wright TW, Zuckerman JD, et al. Rate of improvement in clinical outcomes

- with anatomic and reverse total shoulder arthroplasty. *J Bone Joint Surg Am* 2017;73(Suppl):S111-7. <https://doi.org/10.2106/JBJS.16.01387>
22. Wilson JD, Khan-Perez J, Marley D, Buttress S, Walton M, Li B, et al. Can shoulder range of movement be measured accurately using the Microsoft Kinect Sensor plus Medical Interactive Recovery Assistant (MIRA) software? *J Shoulder Elbow Surg* 2017;26:e382-9. <https://doi.org/10.1016/j.jse.2017.06.004>
23. Wong SE, Zhang AL, Berliner JL, Ma CB, Feeley BT. Preoperative patient-reported scores can predict postoperative outcomes after shoulder arthroplasty. *J Shoulder Elbow Surg* 2016;25:913-9. <https://doi.org/10.1016/j.jse.2016.01.029>
24. Workman CD, Thrasher TA. Validity and reliability of two protocols for measuring reachable workspace volume in able-bodied and stroke subjects. *Technol Health Care* 2016;24:513-21. <https://doi.org/10.3233/THC-161146>
25. Xu X, Robertson M, Chen KB, Lin JH, McGorry RW. Using the Microsoft Kinect™ to assess 3-D shoulder kinematics during computer use. *Appl Ergon* 2017;65:418-23. <https://doi.org/10.1016/j.apergo.2017.04.004>