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ORIGINAL RESEARCH

# Ten-Year Outcomes of Modular Reverse Shoulder Arthroplasty Assessed by 3D Motion Analysis

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**Introduction:** Modular reverse total shoulder arthroplasty (RSA) is a widely accepted treatment for cuff tear arthropathy (CTA), aimed at alleviating pain and improving range of motion (ROM). However, objective long-term data on RSA's impact on activities of daily living (ADL) are sparse. This study is the first to evaluate maximum ROM and ADL performance 10 years after RSA using a 3D motion analysis model.

**Materials and Methods:** A case control study with a total of 29 patients with RSA was divided into two groups: 14 patients with an average follow up of 10 years (long-term group) and 15 patients with a follow-up after 6 months (postoperative group). 3D motion analysis was conducted using a Vicon measurement system and HUX shoulder model. Maximum ROM and activity-related ROM (AROM) were assessed during predefined ADLs. Statistical analyses included independent *t*-tests, calculation of effect sizes (Cohen's d), and adjustment for age and sex using ANCOVA with Bonferroni correction for multiple comparisons.

**Results:** At year follow-up, patients demonstrate only slightly lower maximum and activity-related ROM compared to patients 6 months after surgery. Significant differences between the two groups were noted for shoulder flexion during "neck grip" (postoperative 87.7 ± 14.3° vs long-term 70.1 ± 24.3°; Δ = 17.6°, p = 0.016, d = 0.86) and "book" (postoperative 76.5 ± 8.9° vs long-term 67.8 ± 10.7°; Δ = 8.7°, p = 0.017, d = 0.58) as well as internal/external rotation during "armpit washing" (postoperative 27.2 ± 13.0 vs long-term 15.9 ± 7.6°; Δ = 11.3°, p = 0.011, d = 0.64) ($p < 0.05$), while other movements showed no significant differences.

**Discussion:** 3D motion analysis revealed comparable maximum ROM and similar range used during ADL following RSA. Long-term deterioration in flexion aligns with previous studies but remains within an acceptable range. The reduced AROM over time may be influenced by natural aging or implant-related factors, though performing ADL was possible.

**Conclusion:** Patients after RSA demonstrate good ROM while being able to perform ADL over the long term. With the exceptions of few outcomes, patients 10 years and 6 months after RSA show similar ROM, with good functionality, underscoring the durability and benefits of RSA in managing CTA. Further research with larger cohorts is recommended to confirm these findings.

**Level of Evidence:** Case control study, Level III.

**Keywords:** modular reverse total shoulder arthroplasty, RSA, cuff tear arthropathy, CTA, osteoarthritis, 3D-motion analysis

## Introduction

Cuff tear arthropathy (CTA) is secondary glenohumeral osteoarthritis accompanied by a significant rotator cuff defect.[1,2] Patients with advanced CTA typically experience pain and limited range of motion (ROM); this results in difficulties performing activities of daily living (ADL). Reverse total shoulder arthroplasty (RSA) is a widely accepted treatment option to restore and improve function in these patients. As first described by Grammont,[3] RSA medializes and inferiorizes the glenohumeral center of rotation, thereby increasing the deltoid muscle's lever arm and enhancing recruitment of the anterior and posterior deltoid fibers to compensate for the compromised rotator cuff. Postoperatively, RSA not only provides pain relief but also enhances shoulder function in CTA,[4–9] though its impact on ADL performance remains uncertain. The Constant Score (CS) is frequently used to assess basic ADL performance subjectively,[10,11] but data on objective 3D motion analysis of ADLs following RSA are sparse. Multiple studies demonstrate that the majority of gains in active range of motion—including forward flexion, abduction, and external

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rotation—occur within the first 6 months following surgery, with a plateau reached by 6 to 12 months.[12,13] Similarly, Cabarcas et al found that patients typically reach maximum medical improvement within one year, showing rapid early recovery but no significant additional gains in range of motion thereafter.[14] Consistent with this, Simovitch et al reported that most improvement occurs within the first six months, with only minimal further progress up to two years, and changes between six and twelve months being clinically insignificant.[13]

In clinical practice as well as most studies, manual goniometry has become the standard method for assessing the active and passive range of motion of a joint. The main advantages of this technique lie in its simplicity and rapid execution. However, angular measurements are influenced both by the examiner and by the subject's body configuration. Consequently, goniometry achieves an accuracy of approximately ±5° to ±10°, and due to its substantial simplification with projection onto a two-dimensional plane, it provides only a limited and insufficiently objective representation of complex joint movements.[15–19] A non-invasive, examiner-independent method for three-dimensional assessment of shoulder joint motion is marker-based 3D motion analysis.[20] This technique enables the evaluation of both static and dynamic movement patterns and allows for the determination of precise joint angles at any given point in time during the measurement. These subtle changes in range of motion or activities of daily living (ADL) performance over time are important for prosthesis design optimization, rehabilitation planning, and long-term patient counseling.

Three-dimensional motion analysis has proven to be a valuable tool in various studies investigating the kinetics of the upper extremity following shoulder surgery.[21–23] The Heidelberg Upper Extremity (HUX) model has been extensively evaluated for its reproducibility, validity, and measurement accuracy, including validation of joint center and axis determination as well as compensation for skin motion artifacts.[24–26] The method used for calculating functional joint centers in gait analysis has successfully been adapted to the shoulder, enabling the determination of both static and dynamic motion sequences and precise joint angles at any point during measurement. Dynamic functional joint axes are defined by continuously referencing the joint centers to the thorax throughout movement. This approach distinguishes the method from previously reported techniques for assessing shoulder range of motion.[27,28]

One methodological challenge inherent to the shoulder's extensive range of motion is the potential occlusion of individual markers as well as skin motion artifacts during measurement, particularly depending on patient body habitus. This limitation can be mitigated by using marker clusters and appropriate software algorithms.[24,29]

Therefore, this study aimed to evaluate long-term active maximum ROM and their translation into ADLs, comparing them to patients 6 months postoperative following RSA in patients with CTA using a 3D motion analysis model. We hypothesized that long-term ROM and performing ADL after RSA would show similar results after 10 years compared to 6 months postoperative. Comparable studies employing 3D motion analysis with a 10-year follow-up are, to our knowledge, not available.

# Materials and Methods

## Patients

A total of 29 patients were recruited at our institution, all of whom had been treated with a modular reverse shoulder prosthesis (Aequalis reversed (long-term) and reversed II (postoperative) shoulder prosthesis (Tornier Inc, USA)) for CTA due to cuff tear arthropathy. In all cases, the deltopectoral approach was used. CTA was diagnosed using clinical examination standard anteroposterior (AP) and lateral radiographs. Criteria and indication for RSA remained the same between the two groups. Inclusion criteria were primary RSA with a functional M. deltoideus. Exclusion criteria were previous arthroplasty or RSA in proximal humerus fractures.

Of these, 14 patients had received a reverse shoulder prosthesis for cuff tear arthropathy more than 6 years ago (Group long-term). The average follow-up time in this study was approximately 10 years. About 29% were left-handed, and 71% were right-handed. About 60% underwent surgery on the dominant shoulder. About 71% of the patients were female. The average age was 78 years (standard deviation 8.2 years).

For comparison, 15 consecutive patients were included who had received a reverse shoulder prosthesis 6 months prior to the motion analysis (Group postop). They were evaluated before and 6 months after surgery. About 60% were left-handed, and 40% were right-handed. About 54% underwent surgery on the dominant shoulder. About 47% of the patients were female. The average age was 69 years (standard deviation 9.9 years).

The study was approved by the Ethics Committee of the University of Heidelberg, Germany (S-456/2018), in accordance with the Declaration of Helsinki of 1975, as revised in 2013. Patients were informed about the procedure and background of the study, and following their consent, they were examined in the motion analysis laboratory equipped with an infrared Vicon measurement system (Vicon Motion System, Oxford, United Kingdom). The Constant-Score, the American shoulder and elbow scores (ASES), and the Quick disability of arm, shoulder and hand (Quick-DASH) score were recorded for each group.

The three-dimensional representation of the shoulder is performed using the Vicon measurement system. This system operates with 12 infrared cameras, each documenting shoulder joint movements at a frequency of 120 Hz. The measurement accuracy of the system is ± 1 mm. According to the manufacturer, the resolution of the cameras is 4 megapixels.

Study participants were fitted with reflective markers. The light reflected by the markers is captured by the cameras. The calculation of the three-dimensional position in space is then carried out by the recording software. A prerequisite for this is that a marker always remains in the field of view of at least two cameras. The data from the cameras is transmitted as a video signal to the measurement computer, where it is processed using a database. Following this, the calculation of a three-dimensional dataset from the recorded two-dimensional camera datasets, and thus the reconstruction process, is performed using Vicon Nexus software (Version 2.8, Vicon Motion Systems Ltd., Oxford, UK, 2018).

Before the first examination, the measurement system must be calibrated once to determine the relative positions of the cameras in the room.

The markers used in this study were small spheres with an 8-mm diameter and an infrared-reflective surface. Some were single markers, consisting only of the sphere, positioned 2 mm above the skin. Others were composed of two spheres connected by a 40-mm rod.

Marker placement was conducted according to the HUX (Heidelberg Upper Extremity) shoulder model, which has been validated in previous studies in consensus with the International Society of Biomechanics.[24,25,30–33] To ensure standardized marker positioning for precise measurements, the markers were placed over palpable anatomical structures, referred to as anatomical landmarks. Each study participant was fitted with a total of 8 cluster markers and 7 single markers. Single markers were placed on the processus spinosus of C7, TH8, incisura jugularis of the sternum, mid portion of the sternum and the processus xiphoideus of the sternum. Furthermore, there was a single marker on the mid portion of the right scapula and one the right dorsal forearm. The cluster markers (bilateral placement) were positioned on the acromion, tuberositas deltoidea of the humerus, the olecranon and the distal dorsal forearm.

The examination is divided into various sections: The first step involves calibration recording with the study participants. This recording is initially performed with arms hanging down, followed by positioning the arms on the knees. Additionally, shoulder abduction/adduction, ante-/extension, and elbow flexion are each captured three times. Subsequently, the maximum range of motion and predefined daily movements of the affected shoulder are examined. The recorded data is then transferred into three-dimensional motion sequences using the UpperX software (Bruttel, H (2020) UpperX, Version 1.0, custom Matlab software (unpublished software); Matlab 2017b (The MathWorks, Natick, USA)). The resulting values were calculated as the angular difference between the humeral axis and the body's longitudinal axis. Joint angles represent thoracohumeral motion as defined by the HUX coordinate system.

## Maximum ROM

During the maximum movement recording, the subject was instructed to start from the initial position, with their hands resting on their knees, and transition into the neutral zero position (standard anatomical posture: the head and trunk are erect, arms hang alongside the body, the thumbs pointing forward, the palms facing medially). From this position, they were asked to perform several movements to their maximum capacity, including flexion and extension of the shoulder joint, abduction of the shoulder joint, internal and external rotation with the arms in a lowered position and elbow bend at 90°, flexion and extension of the elbow joint, and finally, pronation and supination of the forearm.

## Activities of Daily Living

The selected ADLs are established movements derived from previous studies that utilize a substantial portion of the available range of motion (ROM) during execution.[32,34,35] The neck grip (hand-behind-neck) and tying an apron (hand-behind-back) tasks are commonly employed in clinical examinations to assess the functional range of motion of the shoulder.

### Tying an Apron (Apron)

Participants were instructed to start from the described initial position with their hands on their knees and then move the hand of the side being examined as far back as possible to touch the middle of the back with the hand. The arm was then returned to the starting position. This movement cycle was repeated five times consecutively for each side.

### Neck Grip (Neck)

Starting from the described initial position, participants were asked to move their hand to the nape, reaching the hairline. The hand was then returned to the starting position. This movement was repeated five times consecutively for each side.

### Washing the Opposite Armpit with a Cloth (Wash)

Participants were given a cloth in the hand of the side being examined. Starting from the described initial position, they were instructed to move the hand to the opposite armpit and perform a single washing motion. The hand was then returned to the starting position. This movement was repeated five times consecutively for each side.

### Retrieving a Book from an Eye-Level Bookshelf (Book)

A height-adjustable, custom-made three-legged structure served as a bookshelf. It was adjusted to the participant's eye level, with a book placed on it at approximately arm's length. Starting from the described initial position, participants were instructed to reach for the book. The empty hand was then returned to the starting position. This movement was repeated five times consecutively for each side.

## AROM

Furthermore, we define the range of motion required for daily activities more accurately using the term "activity-related range of motion" (AROM).[36] Maximum and minimum values for each daily activity for each group were determined. AROM represents the range of motion between the highest maximum value and the lowest minimum value across all ADL in relation to each specific plane of motion.

## Statistical Analysis

The collected kinematic data were exported using the software MatLab (MATLAB 2013, Version R2013a, Natick, Massachusetts: The MathWorks Inc). The statistical analysis was performed using Microsoft Excel (Microsoft Office 2019, Version 2305, Redmond, Washington) and SPSS Statistics Version 20 (SPSS GmbH Software, München, Deutschland). P values < 0.05 were acknowledged as significant. To account for multiple testing, Holm-Bonferroni correction was applied within each analysis family (maximum ROM and Range during ADL). The distribution of the data was evaluated using the Shapiro–Wilk test, and Levene's test was applied to assess the homogeneity of variances. To assess the significance of the difference in ROM in both groups an independent samples *t*-test was applied. To quantify the magnitude of between-group differences, Cohen's *d* effect sizes were computed. In addition, potential confounding effects of age and sex were controlled for by applying an analysis of covariance (ANCOVA). The minimal clinically important difference (MCID) was estimated using a distribution-based method based on the preoperative values of the postop group.

# Results

Postoperatively, the QuickDASH averaged 38.1 ± 21.8 compared to 28.9 ± 22.8 in the long-term group. The mean difference of 9.2 points favored the long-term group, exceeding the MCID (4.4) but without statistical significance ($p = 0.13$), indicating a clinically relevant but non-significant improvement over time.

The ASES score was 69.4 ± 18.4 postoperatively and 65.8 ± 19.4 long-term (Δ = 3.6; p = 0.30), remaining below the MCID (8.3) and thus not clinically relevant.

For the Constant score, values were 53.3 ± 14.5 versus 58.7 ± 14.0 (Δ = −5.4; p = 0.85), also below the MCID (6.2), showing a non-significant and clinically irrelevant difference favoring the long-term group.

## MAX ROM

Range of motion (ROM) was compared between the postoperative and long-term group, using analysis of covariance (ANCOVA, $p_1$) adjusted for age and sex. The long-term group was on average about nine years older than the postoperative group.

This age difference is statistically significant (p = 0.004) and therefore justifies the use of age adjustment in all comparative analyses. All values are reported as mean ± standard deviation (SD) with 95% confidence intervals (CI), see Figure 1 for maximal values of the different motions and Figure 2 for the reached angle of the motion over time.

Mean flexion was 120.2 ± 16.0° (95% CI [111.9; 128.4]) in the postoperative group and 112.1 ± 14.8° (95% CI [103.8; 120.3]) in the long-term group.

The mean difference of 8.1° did not reach statistical significance (p = 0.08) but corresponded to a moderate effect size (d = 0.54). The adjusted group difference was 7.6° and not statistically significant ($p_1$ = 0.08).

Extension averaged –29.2 ± 9.6° (95% CI [–34.3; –24.0]) in the postoperative group and –28.1 ± 9.0° (95% CI [–32.9; –23.3]) in the long-term group.

The mean difference of 1.0° was not significant (p = 0.41) and showed a negligible effect size (d = –0.08). The adjusted extension values differed by 0.8° ($p_1$ = 0.41).

The mean abduction was 104.9 ± 18.2° (95% CI [96.9; 112.9]) for the postoperative group and 105.8 ± 18.5° (95% CI [97.7; 113.8]) for the long-term group.

The difference of 0.9°, with higher values in the long-term group, was not statistically significant (p = 0.46) with a trivial effect size (d = –0.04). The adjusted difference for was 5.6°, which did not reach significance ($p_1$ = 0.72).

The postoperative group showed a mean internal rotation of 24 ± 20° (95% CI [12.9; 35.1]) compared with 19 ± 17° (95% CI [9.2; 28.8]) in the long-term group.

The mean difference was +5.0° which was not statistically significant (p = 0.24) and corresponded to a small effect size (Cohen's d = 0.27). Adjusted internal rotation was 2.0° greater in the postoperative group ($p_1$ = 0.42).

Mean external rotation was 7 ± 25° (95% CI [−7.4; 21.4]) postoperatively versus 13 ± 38° (95% CI [−8.0; 34.0]) in the long-term group.

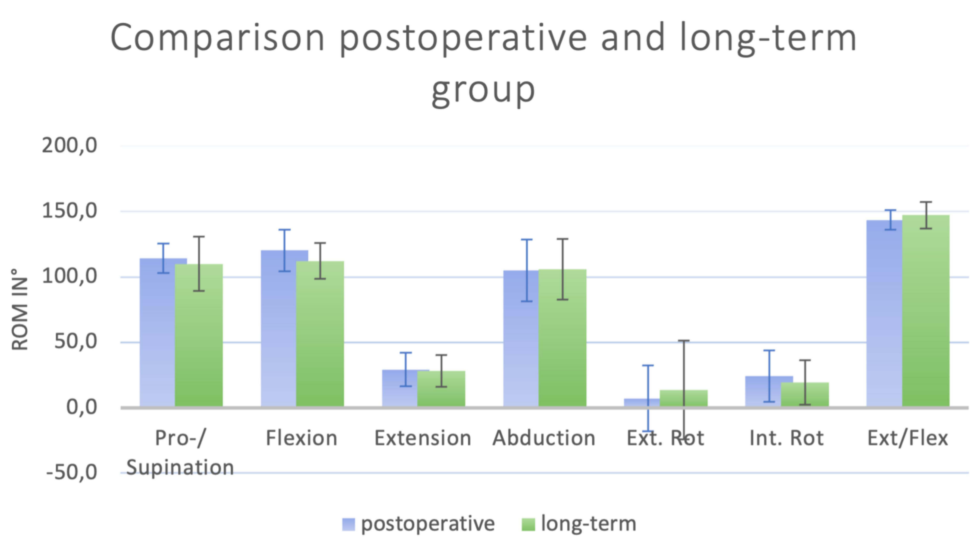


**Figure 1** Comparison of postoperative (blue) to long-term (green) ROM in maximum ROM movements. No significant differences were observed.

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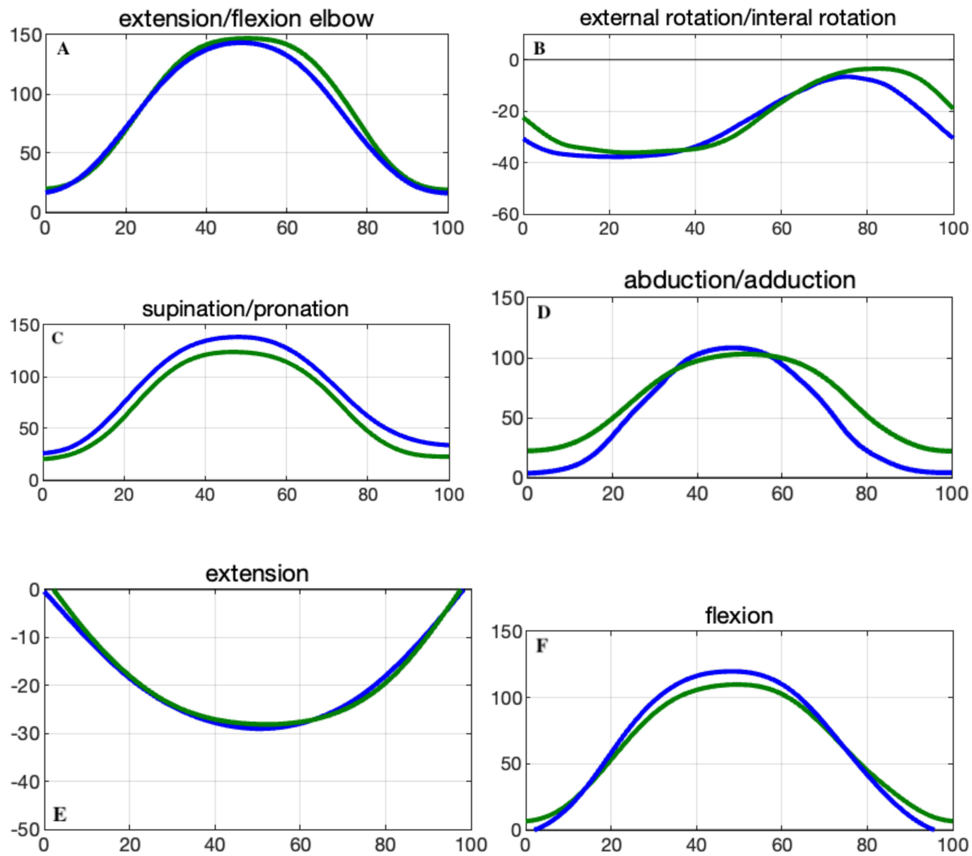


**Figure 2** Range of motion over time. x-axis represents % of the movement, y-axis angle in °; postoperative (blue), long-term (green). (**A**) elbow extension/flexion, (**B**) external and internal rotation of the shoulder (**C**) Supination/Pronation movements start from Max supination into max pronation and back (**D**) abduction and adduction of the shoulder (**E**) extension of the shoulder (**F**) forward flexion of the shoulder. All movements except supination/pronation start from neutral position.

The mean difference was −6.0°, not statistically significant (p = 0.31), and indicated a small effect size (Cohen's d = 0.19), adjusted external rotation was 3.0° greater ($p_1$ = 0.39).

The total ex-/flexion arc measured 143.6 ± 15.3° (95% CI [135.8; 151.3]) postoperatively and 147.1 ± 15.0° (95% CI [139.5; 154.8]) in the long-term group.

The mean difference of 3.5°, with higher values in the long-term group, was not statistically significant (p = 0.14) and corresponded to a small effect size (d = –0.40), the adjusted mean difference was 5.4° ($p_1$ = 0.17).

The postoperative group showed a mean pro-/supination of 114.2 ± 18.7° (95% CI [105.7; 122.7]) compared with 109.8 ± 15.9° (95% CI [101.9; 117.6]) in the group.

The mean difference of 4.4° was not statistically significant (p = 0.24), with a small effect size (Cohen's d = 0.27). The adjusted group difference was 4.2° was not statistically significant ($p_1$ = 0.24).

MCIDs were 9.4° for pro-/supination, 18.0° for flexion, 7.1° for extension, 12.9° for abduction, 5.6° for ex-/flexion arc, 11.7° for internal rotation, and 15.2° for external rotation.

Across all motion planes, no statistically significant differences in ROM were found between the postoperative and long-term groups (p > 0.05). The observed effect sizes (Cohen's d = 0.19–0.54) indicate small to moderate magnitudes of difference. Flexion, pro- and supination as well as internal rotation tended to be slightly higher in the postoperative group, whereas abduction, external rotation and the combined ex-/flexion arc were marginally greater in the long-term cohort.

After adjusting for age and sex using ANCOVA, no motion parameter showed a statistically significant difference between the postoperative and long-term groups (Cohen's d ≈ 0.2–0.3).

When comparing these adjusted differences to the MCIDs derived from the preoperative data of the postoperative group, none of the observed changes exceeded the thresholds for clinical relevance.

## ADL

All patients were able to perform all ADLs. All values are reported as mean ± standard deviation (SD), reached range can be seen in Table 1. Significant differences in shoulder mobility between the postoperative cohort and the long-term follow-up cohort were found for several activities of daily living (ADLs). In the external–internal rotation plane, the wash task showed a markedly greater range of motion in the postoperative group (27.2 ± 13.0°) compared with the long-term cohort (15.9 ± 7.6°; Δ = 11.3°, p = 0.011, d = 0.64), see Figures 3 and 4. In the flexion–extension plane, the book activity also demonstrated a significantly larger range (76.5 ± 8.9° vs 67.8 ± 10.7°; Δ = 8.7°, p = 0.017, d = 0.58). The neck-grip movement, representing a combined elevation and rotation task, showed the most pronounced difference, with a postoperative range in the flexion–extension plane of 87.7 ± 14.3° compared to 70.1 ± 24.3° in the long-term group (Δ = 17.6°, p = 0.016, d = 0.86). Moreover, the maximum flexion angle during the neck-grip task was significantly higher at six months (108.5 ± 16.4°) than at long-term follow-up (93.5 ± 25.0°; Δ = 18.7°, p = 0.016, d = 0.85), see Figures 5 and 6. All these effects remained significant after adjustment for age and sex using ANCOVA, indicating that the observed differences were independent of demographic influences.

After Holm-Bonferroni correction for multiple ADL comparisons (12 tests, adjusted significance threshold $p < 0.0042$), none of the initially significant unadjusted differences remained statistically significant.

In the rotational and sagittal planes, no additional ADL tasks demonstrated significant differences.

Similarly, in the frontal plane (abduction–adduction), no statistically significant differences were observed, see Figures 7 and 8. The largest difference was observed during the neck-grip (82.0 ± 15.4° vs 67.7 ± 32.3°; Δ = 14.3°, p = 0.0812; adjusted Δ = 11.3°, p = 0.1023), whereas the wash task showed slightly higher values in the long-term group (36.7 ± 15.1° vs 44.8 ± 21.5°; Δ = −8.1°, p = 0.1714). All other tasks (apron-tying, book) demonstrated comparable abduction ranges (p > 0.15).

## AROM

While examining the AROM, no significant differences between the two groups were observed, with a deterioration over time for the long-term group, see Figure 9.

Postoperatively, an AROM (activity-related range of motion) of 140° was determined in the plane of "flexion/ extension". The maximum value for flexion was observed during the daily activity "neck grip", while the greatest value for extension was recorded during the "apron" movement.

The long-term group exhibited an AROM of 124°. The maximum values for flexion were also recorded during the "neck grip" and for extension during the "apron".

Postoperatively, an AROM of 111° was determined in the plane of "abduction/adduction". The maximum abduction was also recorded during the "neck grip", and the maximum adduction was achieved during the "armpit washing" movement.

The long-term group achieved an AROM of 104°. The maximum value for abduction was reached during the movement "retrieving a book from a shelf", while the maximum adduction was also recorded during the daily activity "armpit washing".

In the postoperative group, an AROM of 148° was reached in the plane of "internal rotation/external rotation". This was based on the maximum value for external rotation, recorded during the "neck grip", and the maximum value for internal rotation, achieved during the "apron grip".

In the long-term group, a total AROM of 146° was measured. These values were also based on the maximum values for external rotation during the "neck grip" and for internal rotation during the "apron grip".

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**Table 1** Range Used During Different ADLs in the Different Planes of Motion for Both Groups

| Motion | Plane | Metric | Postop Mean ± SD | LT Mean ± SD | Δ (Postop–LT) | Cohen's d | P (Unadjusted) | Δ (Adj Age+Sex) | P (Adjusted) |
|---|---|---|---|---|---|---|---|---|---|
| Apron | Abd–Add | Range | 15.6 ± 3.8 (95% CI [13.5. 17.7]) | 16.5 ± 7.1 (95% CI [12.6. 20.4]) | −0.9 | –0.15 | 0.3847 | −1.8 | 0.3929 |
| Apron | Ext–Int Rot | Range | 91.0 ± 30.8 (95% CI [73.9. 108.1]) | 86.6 ± 20.3 (95% CI [75.4. 97.8]) | 4.4 | 0.16 | 0.3562 | 6.5 | 0.3348 |
| Apron | Flex–Ext | Range | 56.8 ± 11.7 (95% CI [50.3. 63.3]) | 58.6 ± 15.1 (95% CI [50.2. 67.0]) | −1.8 | –0.14 | 0.3821 | 2.1 | 0.3477 |
| Book | Abd–Add | Range | 73.6 ± 39.2 (95% CI [51.9. 95.3]) | 71.5 ± 32.6 (95% CI [53.4. 89.6]) | 2.1 | 0.08 | 0.4655 | 0.5 | 0.4829 |
| Book | Ext–Int Rot | Range | 47.6 ± 19.0 (95% CI [37.1. 58.1]) | 40.7 ± 15.3 (95% CI [32.2. 49.2]) | 6.9 | 0.32 | 0.2145 | 7.3 | 0.2011 |
| Book | Flex–Ext | Range | 76.5 ± 8.9 (95% CI [71.6. 81.4]) | 67.8 ± 10.7 (95% CI [61.9. 73.7]) | 8.7 | 0.58 | 0.0174 | 8.5 | 0.0182 |
| Neck Grip | Abd–Add | Range | 82.0 ± 15.4 (95% CI [73.5. 90.5]) | 67.7 ± 32.3 (95% CI [49.8. 85.6]) | 14.3 | 0.59 | 0.0812 | 11.3 | 0.1023 |
| Neck Grip | Ext–Int Rot | Range | 61.4 ± 27.4 (95% CI [46.2. 76.6]) | 60.8 ± 22.2 (95% CI [48.5. 73.1]) | 0.6 | 0.02 | 0.4911 | 0.6 | 0.491 |
| Neck Grip | Flex–Ext | Range | 87.7 ± 14.3 (95% CI [79.8. 95.6]) | 70.1 ± 24.3 (95% CI [56.6. 83.6]) | 17.6 | 0.86 | 0.016 | 17.2 | 0.0415 |
| Wash | Abd–Add | Range | 36.7 ± 15.1 (95% CI [28.3. 45.1]) | 44.8 ± 21.5 (95% CI [32.9. 56.7]) | −8.1 | –0.38 | 0.1714 | −9.8 | 0.1591 |
| Wash | Ext–Int Rot | Range | 27.2 ± 13.0 (95% CI [20.0. 34.4]) | 15.9 ± 7.6 (95% CI [11.7. 20.1]) | 11.3 | 0.64 | 0.0112 | 11.5 | 0.0109 |
| Wash | Flex–Ext | Range | 34.8 ± 9.9 (95% CI [29.3. 40.3]) | 34.4 ± 9.1 (95% CI [29.4. 39.4]) | 0.4 | 0.03 | 0.4875 | 0.3 | 0.4881 |

**Note**: p-values and age and sex-adjusted p-values.

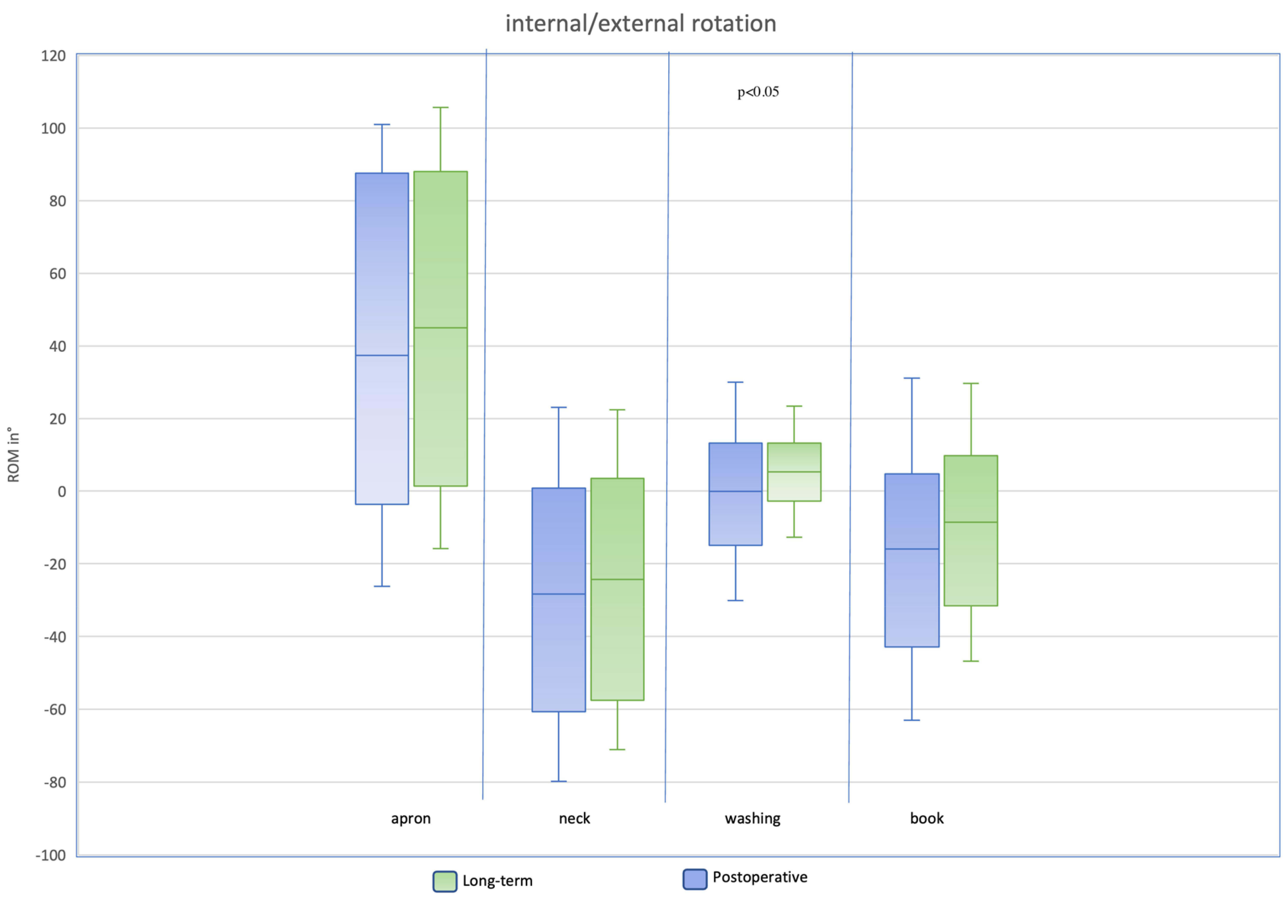


**Figure 3** Comparison of postoperative (blue) to long-term (green) range in internal and external rotation in ADLs, y-axis in °; Internal rotation are positive values; external rotation are negative values. Significant differences were found for washing, with similar range used during book, neck and apron.

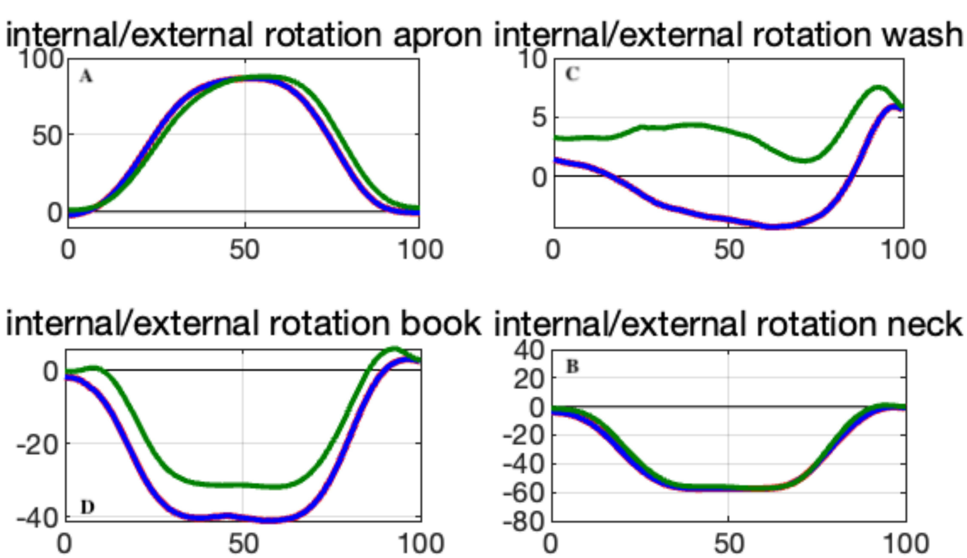


**Figure 4** Internal and external rotation (in ° on y-axis) over % of the movement on x-axis, postoperative (blue), long-term (green); Internal rotation are positive values; external rotation are negative values during (**A**) tying an apron, (**B**) neck grip, (**C**) washing the opposite armpit with a cloth, (**D**) retrieving a book from an eye-level bookshelf.


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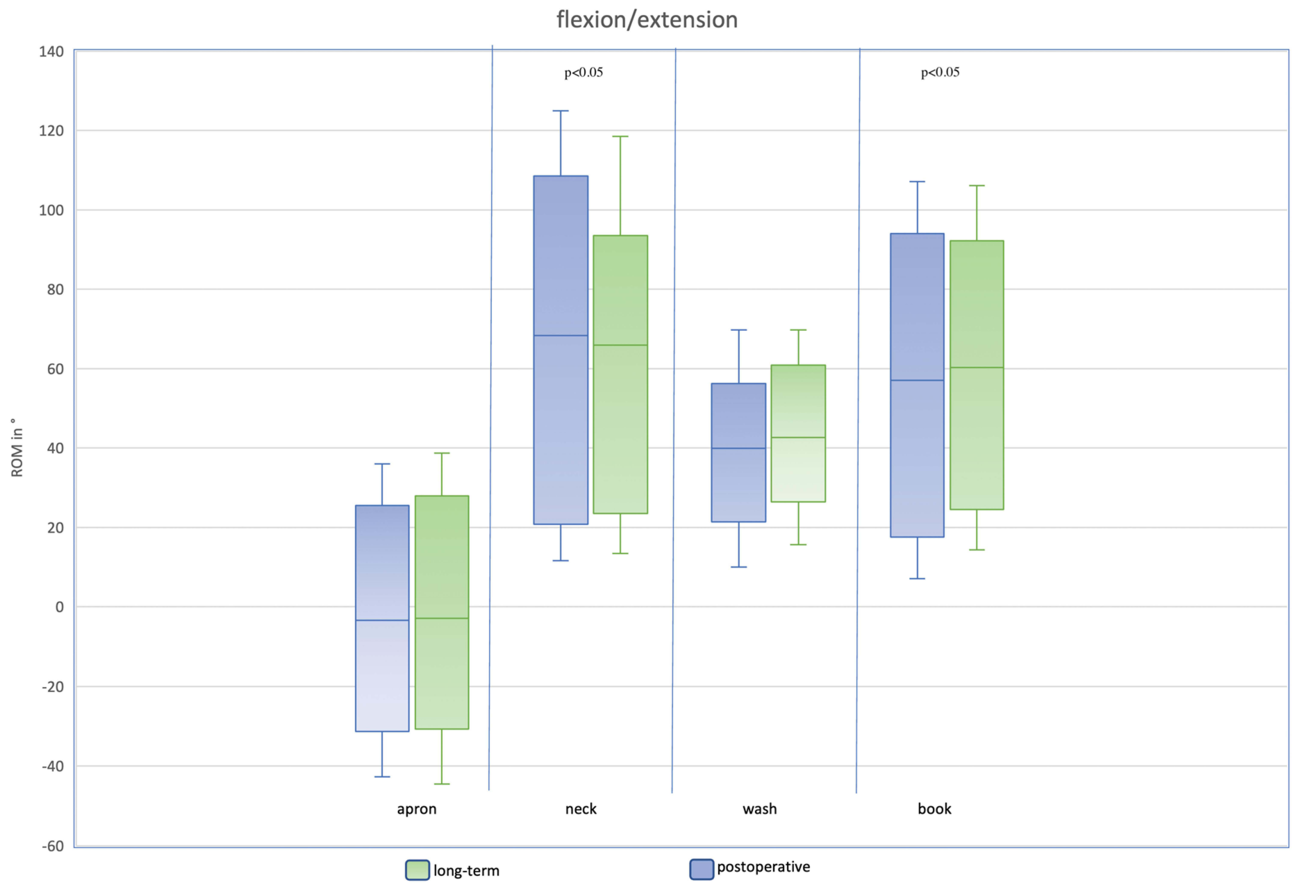


**Figure 5** Comparison of postoperative (blue) to long-term (green) range in flexion in ADLs, y-axis in °, significant greater range used in the postoperative group for book and neck, while a similar range is used for washing and apron.

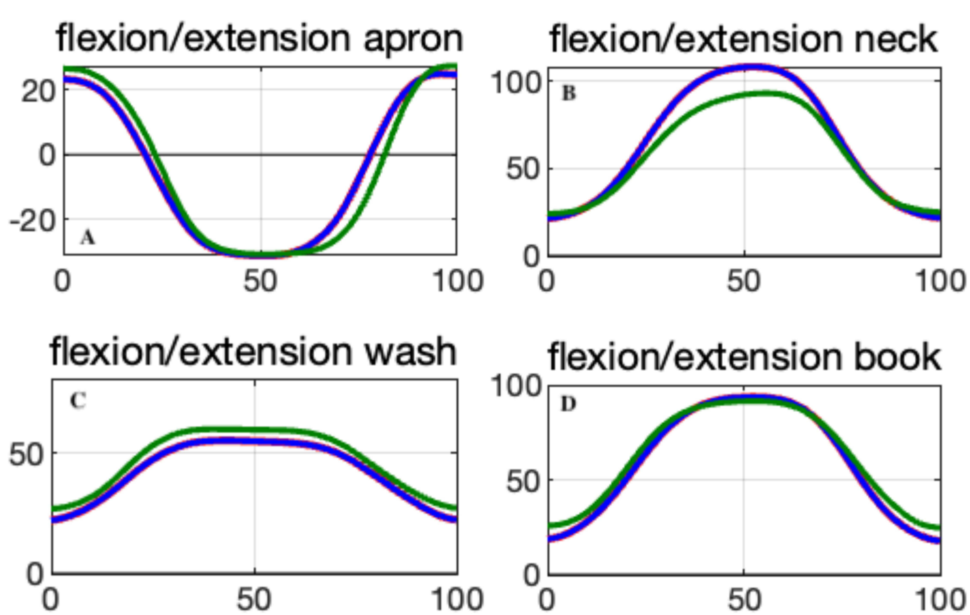


**Figure 6** Flexion (in ° on y-axis) over % of the movement on x-axis, postoperative (blue), long-term (green); flexion are positive values; extension are negative values during (**A**) tying an apron, (**B**) neck grip, (**C**) washing the opposite armpit with a cloth, (**D**) retrieving a book from an eye-level bookshelf.

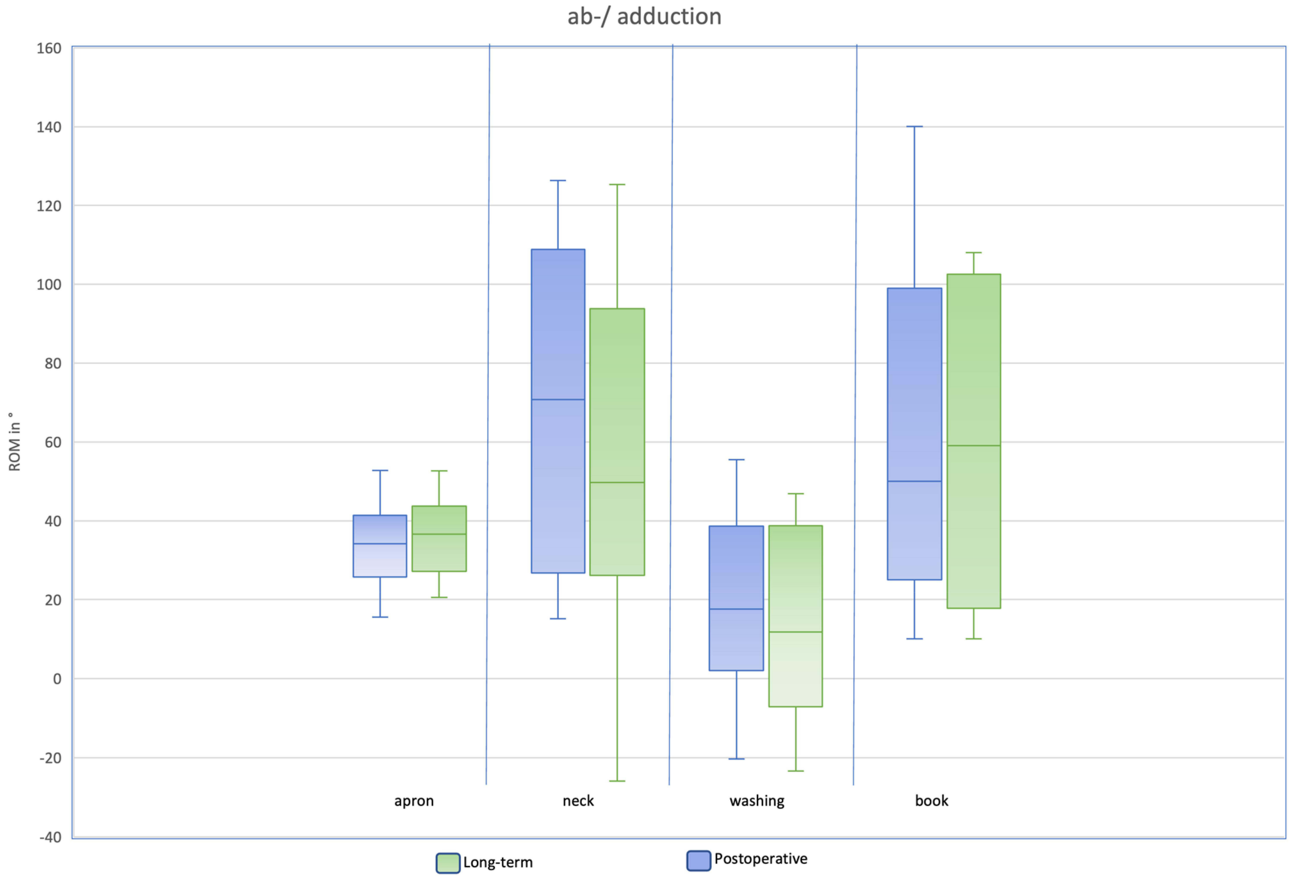


**Figure 7** Comparison of postoperative (blue) to long-term (green) range in abduction in ADLs, y-axis in °: no significant difference was found between the two groups.

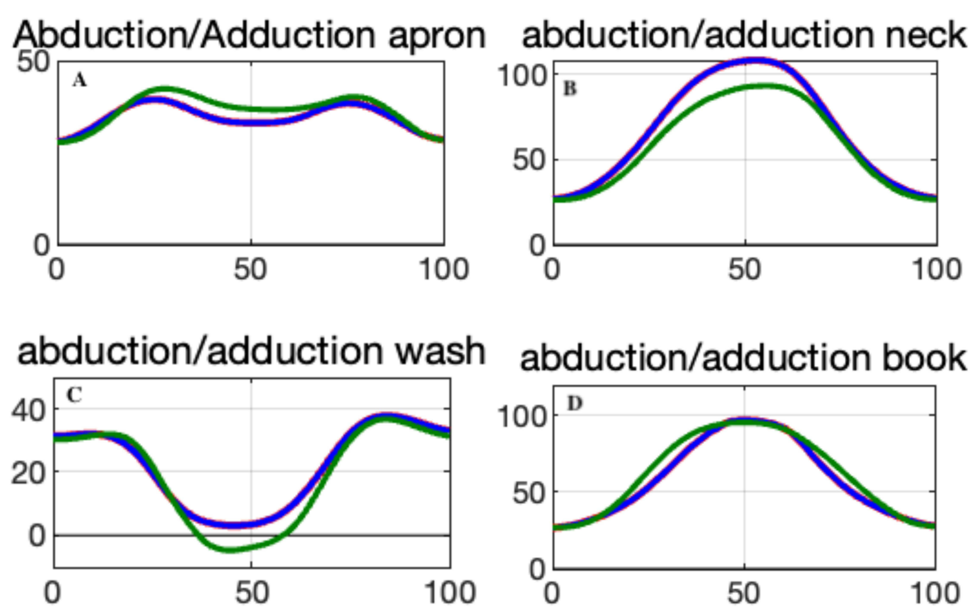


**Figure 8** Adduction/Abduction (in ° on y-axis) over % of the movement on x-axis, postoperative (blue), long-term (green); Abduction are positive values; Adduction are negative values during (**A**) tying an apron, (**B**) neck grip, (**C**) washing the opposite armpit with a cloth, (**D**) retrieving a book from an eye-level bookshelf.

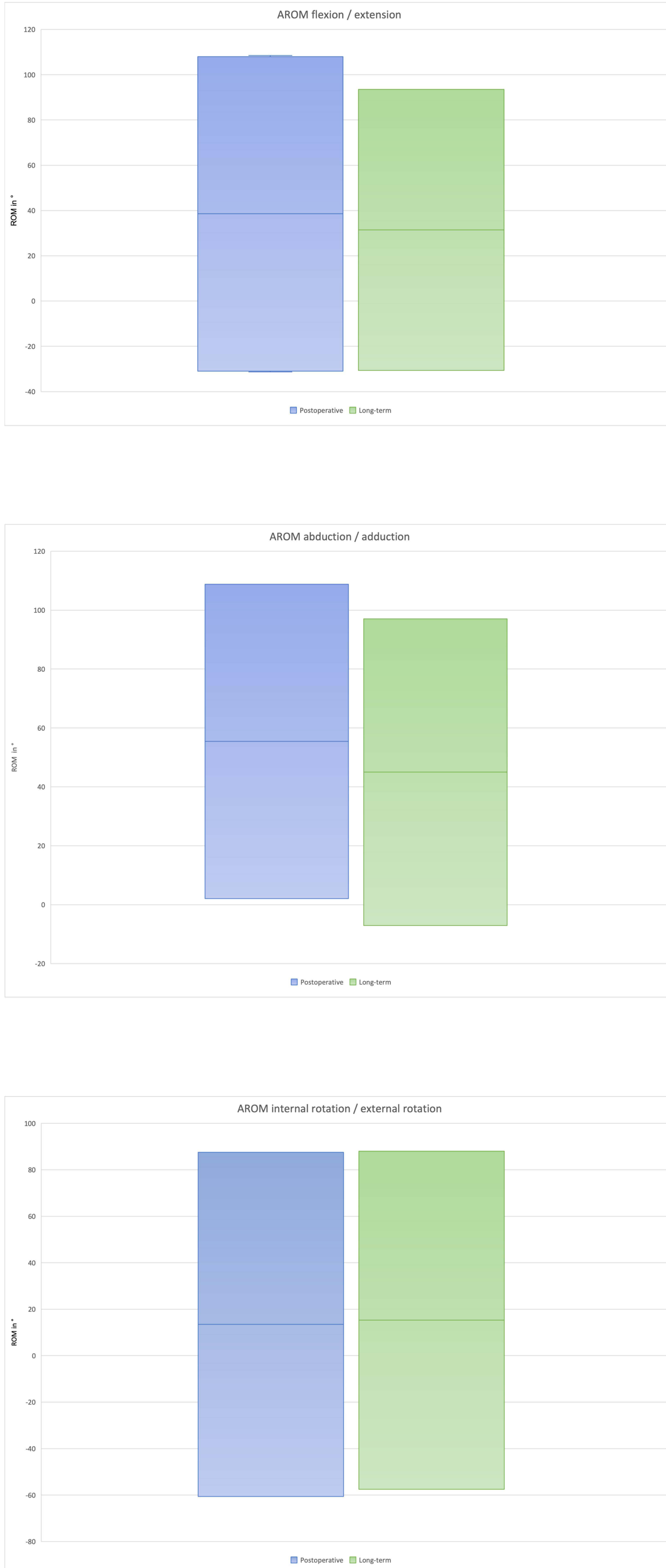


**Figure 9** AROM for flexion/extension, adduction/abduction and internal/external rotation; blue (postoperative) and green (long-term); no significant difference between the two groups.

## Discussion

In our study, there were no significant differences in the Max-ROM between the two groups, while the postoperative group showed greater ROM in some motions (Flexion, pro- and supination as well as internal rotation), while the long-term group in others (abduction, external rotation and the combined ex-/flexion arc). None of the differences reached clinical significance, with all mean difference below the MCID. As the postoperative cohort in the present study was evaluated approximately six months after surgery, the results primarily reflect the early phase of functional recovery following reverse shoulder arthroplasty. It is established that most of the postoperative improvement in range of motion and daily activity performance occurs within this time frame, largely due to pain reduction, early rehabilitation gains, and restoration of deltoid function. However, several longitudinal studies have demonstrated that continued, albeit slower, improvements in shoulder mobility, strength, and proprioceptive control may occur up to two years postoperatively.[12–14] Therefore, while the current findings likely capture the main phase of early recovery, they may slightly underestimate the final long-term functional potential of these patients.

Multiple studies show that the average postoperative active flexion is 125.4° (range 71°–144.5°).[37–39] Our post-operative measured maximum flexion, at 120.15°, falls within the range. In the long-term group, a non-significant reduction in flexion was observed over an average postoperative period of 10 years. In a long-term study by Raiss et al, a reduction in flexion to an average of 124° was demonstrated 9–14 years after reverse shoulder prosthesis implantation.[40] Another long-term study showed a decrease in flexion to an average of 131° after 10 years.[41] In our study, the flexion was 112° on average after 10 years, which is below the reported values. A possible explanation is that the measurement in 3D analysis is more precise. Flexion involves a combination of glenohumeral and scapulothoracic movements. Without a 3D-motion analysis, it is challenging to effectively distinguish glenohumeral joint movement from compensatory motions of the shoulder girdle or trunk. It is likely that scapulothoracic motion, and potentially compensatory trunk movements, were included in the reported measurements in these clinical studies. Additionally, studies have shown that patients with massive cuff tear arthropathy tend to have worse short-term postoperative outcomes. The significant further deterioration in long-term outcomes has not yet been adequately explained.[41]

The 3D motion analysis of the upper extremity using the extended HUX model allows for the measurement of joint angles for flexion/extension, abduction/adduction, pronation/supination, and elbow extension/flexion at any given time during complex dynamic movements of daily activities involving the upper extremity. Two descriptions of the range of motion for daily activities are used. The "Range of Motion" (ROM) refers to the range of motion ROM calculated as the difference between the mean values of all maximum and minimum values of the four daily activities for all study participants. The ROM pertains to a specific movement plane of a given daily activity. The AROM (activity-related range of motion), the range of motion between the highest mean maximum value and the lowest mean minimum value across all four daily activities (in relation to a specific movement plane), provides an overall estimate of functional joint use in daily activities.[36]

When comparing ROM during ADL of the postoperative group with the long-term group, significant differences with higher values in the postoperative group were found for flexion in "neck grip" and "book" as well as rotation in "armpit washing", no significant changes in the range of motion were observed for the apron grip.

When considering AROM, no significant results were found for the individual ranges of motion. However, a general trend towards deterioration in the long-term group was noted in all movements.

To date, there are few studies that investigate the 3D range of motion in daily activities after the implantation of a reverse shoulder prosthesis. Maier et al studied ROM in a small group of subjects one year after the implantation of a reverse shoulder prosthesis and, as in this study, observed improvements in flexion and abduction during the performance of activities of daily living (ADLs). The ADLs performed in that study were similar to the ADLs in this study. Not all patients were able to perform all ADLs one year postoperative, although achieving similar ROM during the ADLs.[32] Compared to the results of Maier et al who found an flexion of 109°, an active abduction of about 94° and active adduction of about 33° one year after RSA the postoperative as well as the long-term group fall well within range.[32]

Comparing to hemiarthroplasty similar results were achieved, with a greater overall ROM (flexion of 127°, abduction 78°). Considering that these patients have an intact rotator cuff, and also a better preoperative ROM, our findings fall within the expected range.[25] The duration of the follow-up differs, as further improvements in mobility can be expected 6 months postoperative.

The active range of motion (AROM) observed in the present analysis exceeded the functional values reported by Raiss et al for all movement planes except rotation.[36] In the postoperative group, mean AROM reached 140° for flexion–extension, 111° for abduction–adduction, and 148° for external–internal rotation, while the long-term group achieved 124°, 104°, and 146°, respectively. When compared to the functional reference ranges reported by Raiss et al (Flex/Ext: 100°, Abd/Add: 89°, Ext/Int Rot: 205°), the current results indicate a slightly higher proportion of motion utilized in the sagittal and frontal planes (≈ 120–140%), whereas rotation reached approximately 70% of the physiological range.

It should also be noted that Raiss et al investigated a different set of ADL tasks and included a substantially younger and healthy volunteer cohort, which likely contributed to the higher absolute AROM values, particularly for rotation. The younger population, free of degenerative or postoperative limitations, typically demonstrates greater soft-tissue elasticity and muscular balance, explaining the broader rotational amplitudes compared to the present postoperative and long-term groups.

Similarly, Triffitt et al evaluated 125 individuals performing 13 daily activities using manual goniometry.[42] They reported a functional requirement of 115° for flexion–extension, 106° for abduction–adduction. Compared to these functional thresholds, both study groups in the current analysis exhibited equal or higher AROM values, particularly for flexion–extension and abduction–adduction, confirming that the cohorts could perform ADL within or beyond the physiological limits defined by prior normative studies. In contrast, the relative reduction in total rotational amplitude (~145–148° vs 205° reported by Raiss et al) highlights the persisting constraint of glenohumeral rotation despite preserved overall shoulder mobility.[36,42]

During the literature review, it became apparent that studies with long-term data on ADL often rely solely on the Constant-Murley score. With longer follow-up times of over 5 years, there is a general reduction in range of motion during activities of daily living,[39] with further deterioration occurring after more than 9 years.[43] The results of the long-term study arm, with a follow-up of 10 years, align with the findings in the literature.

A significant difference in the mean age between the two groups was observed. Part of the variation in the measured outcomes is likely attributable to age-related degenerative changes. When adjusting the values for age and sex, no clinically relevant differences remain between the groups.

Progressive decline in shoulder function with aging results from a multifactorial interplay of degenerative alterations in the rotator cuff tendons, age-related muscular atrophy and fatty infiltration, decreased shoulder mobility, and the onset of glenohumeral osteoarthritis.

Age-associated degenerative changes within the rotator cuff—including tendinopathy as well as partial- and full-thickness tears—are strongly linked to advancing age and are frequently observed even in asymptomatic individuals, representing a physiological component of the aging process rather than purely pathological findings.[44,45] These alterations are accompanied by a reduction in abduction strength and shoulder range of motion, particularly internal rotation, as demonstrated in large normative cohorts of healthy adults.[46] Concurrent muscle atrophy and fatty degeneration, predominantly affecting the supraspinatus and subscapularis, further diminish shoulder stability and functional capacity, and can occur even in the absence of evident tendon disruption.[47,48]

Biomechanical investigations have consistently shown that older adults exhibit markedly reduced shoulder strength, leading to a greater relative muscular demand during activities of daily living and contributing to functional decline and pain.[49]

Overall, age- and sex-adjusted analyses confirm that both groups exhibited comparable shoulder motion patterns. Minor directional trends (slightly greater flexion and rotation in the postoperative group, and somewhat higher abduction and motion arc in the long-term group) did not reach statistical significance and correspond to small effect sizes. These findings suggest that long-term functional shoulder motion remains well preserved following surgery, without clinically relevant decline over time.

## Limitations and Future Directions

This study has several limitations that should be acknowledged. The relatively small sample size may have limited the statistical power to detect subtle yet clinically meaningful differences between groups. Therefore, some of the observed trends should not necessarily be interpreted as a lack of difference, but rather as an indication of potential underpowering due to limited cohort size. Moreover, the retrospective nature of the study and the absence of a control group with the contralateral or a healthy shoulder restrict the generalizability of the findings and potentially leading to a selection bias. Moreover, as the postoperative cohort represents an early follow-up stage, a further improvement in range of motion and functional adaptation over time can be expected. Additionally, some of the recorded difference may be attributed to a different prosthesis design.

Future studies should therefore aim to include larger, prospectively designed cohorts and longer-term multiple timepoint follow-up (6 months, 2 years, 5 years) to confirm these findings and further elucidate compensatory movement strategies over time. Comparative analyses with propensity-matched control groups and correlation with patient-reported outcome measures could also help to establish the clinical relevance of the subtle kinematic changes observed in this study. Adding the evaluation of the non-affected side, the natural deterioration of shoulder function can be used for comparison. Finally, integrating electromyographic or kinetic data may provide a more comprehensive understanding of neuromuscular adaptations after reverse shoulder arthroplasty.

## Conclusion

This study represents one of the few long-term (10 years follow-up) investigations to objectively quantify functional outcomes of reverse shoulder arthroplasty using 3D motion analysis. Our findings demonstrate that the range of motion achieved early after surgery differs only slightly from that observed a decade later and does not limit the performance of daily activities.

These results provide robust evidence for the functional durability of modular RSA in cuff tear arthropathy and offer valuable benchmarks for patient counseling, prosthesis design optimization, and targeted rehabilitation strategies.

## Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used generative AI-LLM for spellcheck and syntax in order to improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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## Disclosure

The authors report no conflicts of interest in this work.

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