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Do Magnets Have the Potential to Serve as a Stabilizer for the Shoulder Joint in Massive Rotator Cuff Tears?: A Biomechanical Cadaveric Study

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Background: Disruption of the rotator cuff muscles compromises concavity compression force, which leads to superior migration of the humeral head and loss of stability. A novel idea of using the magnetic force to achieve shoulder stabilization in massive rotator cuff tears (MRCTs) was considered because the magnets can stabilize two separate entities with an attraction force. This study aimed to investigate the biomechanical effect of the magnetic force on shoulder stabilization in MRCTs.

Methods: Seven fresh frozen cadaveric specimens were used with a customized shoulder testing system. Three testing conditions were set up: condition 1, intact rotator cuff without magnets; condition 2, an MRCT without magnets; condition 3, an MRCT with magnets. For each condition, anterior-posterior translation, superior translation, superior migration, and subacromial contact pressure were measured at 0°, 30°, and 60° of abduction. The abduction capability of condition 2 was compared with that of condition 3.

Results: The anterior-posterior and superior translations increased in condition 2; however, they decreased compared to condition 2 when the magnets were applied (condition 3) in multiple test positions and loadings ($p < 0.05$). Abduction capability improved significantly in condition 3 compared with that in condition 2, even for less deltoid loading ($p < 0.05$).

Conclusions: The magnet biomechanically played a positive role in stabilizing the shoulder joint and enabled abduction with less deltoid force in MRCTs. However, to ensure that the magnet is clinically applicable as a stabilizer for the shoulder joint, it is necessary to thoroughly verify its safety in the human body and to conduct further research on technical challenges.

Keywords: *Massive rotator cuff tear, Anatomical shoulder arthroplasty, Magnet, Stabilization, Biomechanics*

The rotator cuff muscles create force couples around the glenohumeral joint and act as dynamic stabilizers of the shoulder joint.[1,2] When a massive rotator cuff tear (MRCT) occurs, the shoulder joint loses its stabilizing function, resulting in the superior migration of the humeral head and breakdown of the glenohumeral joint.[3] Eventually, it can progress to more severe problems such as pseudoparalysis and arthropathy, in which degenerative arthritic changes of the glenohumeral joint occur.[4]

To date, reverse total shoulder arthroplasty (RTSA) has been widely accepted as the most promising treatment option for severe glenohumeral arthritis with cuff deficiency. Since Paul Grammont developed the modern RTSA in 1985, numerous satisfactory results have been reported.[5-7] Although RTSA is an innovative treatment that can restore active arm elevation, relieve pain, and improve shoulder function in most patients with cuff deficiency,

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there are still several inherent challenges due to the non-anatomical design, such as notching, rotation limitation, neurologic complications from arm lengthening, and acromial fracture due to tension from the deltoid muscle.[8,9] To overcome these limitations, implants associated with the concept of lateralization of the glenoid or humerus side have been developed, and several positive results have been reported.[10] However, the fundamental challenges resulting from the non-anatomical design of RTSA remain.

In 2012, superior capsule reconstruction (SCR) was introduced as a surgical option for treating an irreparable MRCT.[11] Since then, the global popularity of SCR has grown rapidly.[12] Furthermore, Mihata et al.[13,14] reported that SCR can eliminate pseudoparalysis and restore the function of the shoulder joint by enhancing superior stability and can be an alternative to RTSA for treating irreparable MRCTs without arthritic changes, and numerous satisfactory outcomes have been reported to support this.[14,15] Theoretically, if the superior migration of the humeral head can be prevented and the stability of the shoulder joint can be maintained as mentioned in the above results, it would be possible for patients with cuff deficiency to elevate the arm again and restore the function.[13] Despite these benefits, SCR is still not indicated for MRCTs accompanied by glenohumeral arthritis, and anatomical shoulder arthroplasty cannot be used in MRCTs because the center of rotation (CoR) is not maintained, making RTSA an inevitable treatment option for cuff arthropathy

Even if it has progressed to arthropathy, if there is an additional device that maintains CoR of the shoulder joint and stabilizes the joint in the cuff-deficient shoulder even with anatomic shoulder arthroplasty, it may be possible to resolve the shortcomings and weakness of RTSA due to non-anatomical design while maintaining normal biomechanics of the shoulder joint. To this end, we contrived a novel idea of using a magnet in MRCTs. We speculated that magnets could achieve shoulder stabilization in MRCTs by partially replacing the compressive force of the rotator cuff because the magnetic force can stabilize two separate entities with a pulling force (Fig. 1).[16] Moreover, the distance between magnets has been proven to be an important factor that affects the strength of the magnetic force.[17] To exert the magnetic force identical to all movements of the shoulder joint, such as flexion, extension, rotation, adduction, and abduction, the magnets placed in the glenoid and humerus should always be equidistant from each other. Hence, we conceived the concept of placing a spherical magnet in the center of the humerus and a coin-shaped magnet in the glenoid. To implement this concept, we devised a simulated humeral implant, where a spherical magnet could be placed at the center of the humeral head using three-dimensional (3D) printing technology. Therefore, this study aimed to biomechanically investigate whether a magnet could act as a shoulder stabilizer in MRCTs, using the devised simulated implant. We hypothesized that the magnet could serve as a stabilizer of the shoulder joint in MRCTs.

METHODS

Magnetic Implant Design

The inlay-type stem and the head component were manufactured using 3D printing technology. A space was created for the spherical magnet to be inserted between the prosthetic humeral head and stem components (Fig. 2), which were manufactured to contain a detachable groove

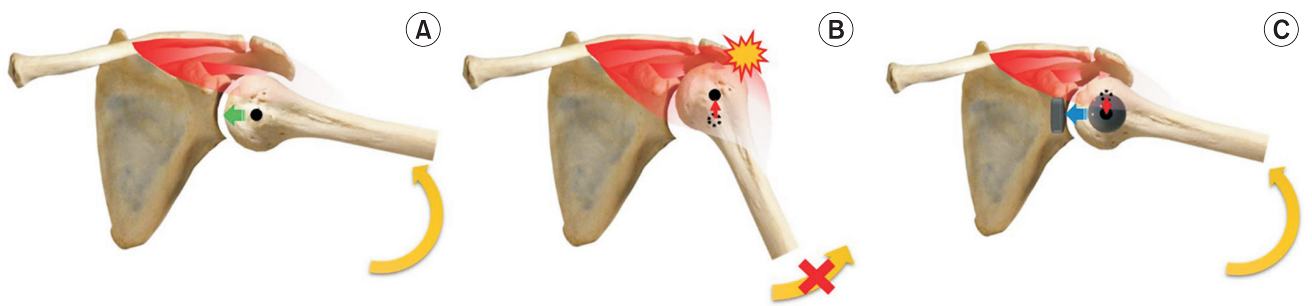


Fig. 1. Schematic diagram showing the biomechanical concept of this study. (A) The intact rotator cuff muscles maintain glenohumeral stability by compressing the humeral head into the glenoid. (B) Irreparable rotator cuff deficiencies create an unstable fulcrum of motion, leading to the superior migration of the humeral head on the glenoid and breakdown of glenohumeral joint biomechanics. (C) The magnetic force inhibits humeral head elevation and helps maintain the center of rotation (CoR), making it easier for the humerus to abduct. Black circle: CoR of the shoulder joint, green arrow: the compressive force of the rotator cuff, yellow arrow: arm movement, black dotted circle: CoR of the shoulder joint before changes, red arrow: change in CoR of the shoulder joint, blue arrow: the pulling force of magnets.

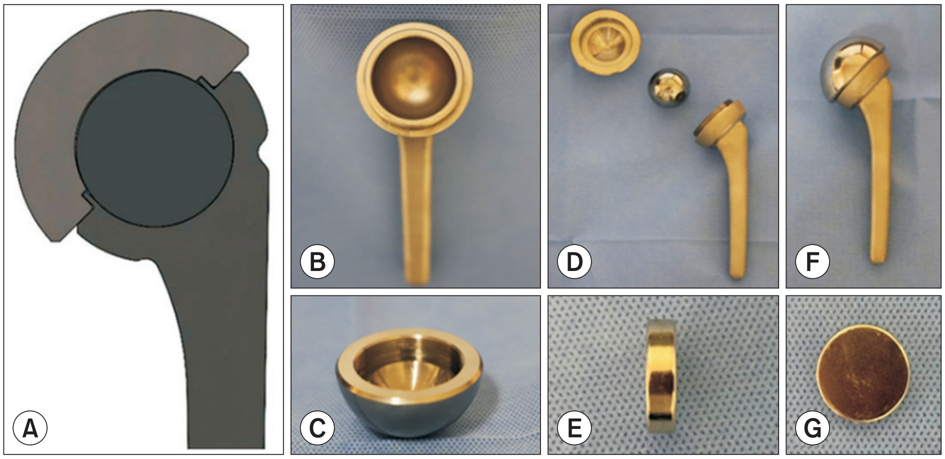


Fig. 2. Humerus implants and magnet. (A) Schematic diagram of the implant that is designed to hold a spherical magnet at the center of the humerus head between the head component and the humeral stem. (B) Humeral stem. (C) Head component. (D) Head component, spherical magnet, and humeral stem before their attachment. (E) Humerus implant after attachment. (F, G) Coin-shaped glenoid magnet.

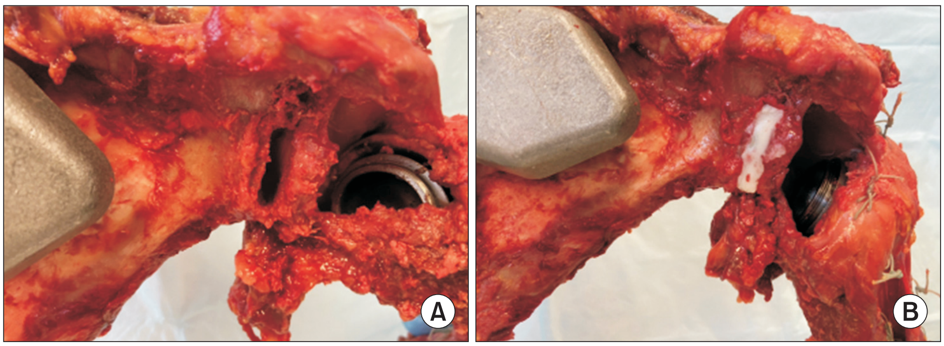


Fig. 3. Insertion of a coin-shaped magnet. (A) Post-ostectomy diagram showing adequate space for the coin-shaped magnet to be placed on the medial side of the glenoid. (B) Insertion of the magnet into the ostectomy site, followed by fixation using cement.

and an open space where a magnet could be inserted and removed with ease. The magnet and humeral stem are designed to be unfixed to allow the arm to move freely in all directions while maintaining the polarity of the spherical magnet. The size of the stem was either 10 mm or 12 mm, depending on the intramedullary isthmus diameter of the cadaver, while the prosthetic humeral head size was 42 mm for all cadavers to maintain the same magnetic effect.

The spherical magnet had a diameter of 25 mm, and the coin-shaped magnet inserted into the glenoid had a thickness of 5 mm and a diameter of 20 mm. Both magnets were made of nickel-coated neodymium. The pulling force between the two magnets was measured to be 8.7 N.

Preparation of Specimens

Seven fresh frozen cadaveric specimens (four right shoulders and three left shoulders) were used. The average age of the specimens was 59.0 ± 9.8 years (range, 46–69 years). There were five shoulders from male cadaver donors and two from female cadaver donors. This study was exempted from institutional review board approval as this was a basic cadaveric study with no identifiers. All specimens used in this study were macroscopically intact with no preexisting rotator cuff tears or abnormalities. The shoulders were dissected free of soft tissue; however, we preserved the capsule, coracoacromial ligament, all rotator cuff tendons, pectoralis major, latissimus dorsi, and deltoid insertions on the humerus. The humeral shaft was then transected 2 cm distal to the deltoid insertion.

For implant insertion, the anterior capsule was incised from the rotator cuff interval to the glenoid in a 5:30 direction, while preserving the muscle insertion site. The humeral head was then dislocated and cut, following the anatomic retroversion for humerus component insertion. As this was a cadaveric study to evaluate the new concept that we had formulated, the magnet on the glenoid side was simply applied via an ostectomy. The ostectomy was performed to insert a coin-shaped magnet on the medial side at 3 mm from the anterior glenoid margin, and the magnet was secured using cement (Fig. 3).

Six small digitizing marker screws were inserted on the specimen, three on the acromion (anterolateral, mid, and posterolateral border) and three on the humeral shaft just posterior to the bicipital groove as markers to quantify the glenohumeral kinematics.[18] The scapula plate was bolted to the infraspinatus fossa with the medial border parallel to the long edge of the mounting bracket. The scapula was mounted on a custom testing system at 20°

anterior tilt and 0° abduction. The humerus was attached to the testing arc by inserting the intramedullary rod into the humeral medullary canal and securing it to the humeral mounting cylinder with screws. The abduction arc was adjusted such that the humerus was positioned in the scapular plane when abducting (Fig. 4). No. 2 fiber-wire (Arthrex, Naples, FL, USA) sutures were placed on the remaining muscle insertion site to apply loading forces onto the muscle (supraspinatus, 2; subscapularis, 2; infraspinatus, 2; teres minor, 1; deltoid, 3; pectoralis major, 2; latissimus dorsi, 2).

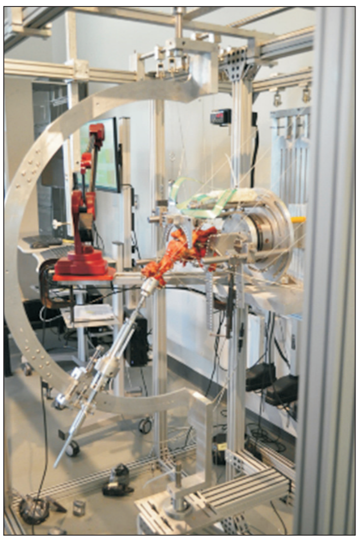


Fig. 4. Customized shoulder testing system used in this study.

Testing Conditions

All biomechanical tests were performed under three conditions: condition 1 (intact condition), intact rotator cuff tendon without magnets; condition 2 (MRCT condition), irreparable MRCT without magnets; and condition 3 (MRCT with magnet condition), irreparable MRCT with magnets. For the MRCT condition, firstly the entire load on the supraspinatus and the upper portion load on the infraspinatus were removed. An MRCT was then created, with both the supraspinatus and superior shoulder capsule incised at their insertions on the greater tuberosity. Incisions were made from the anterior border to the posterior border of the supraspinatus–superior capsule at the greater tuberosity and continued medially along the posterior border of the supraspinatus. For MRCT with magnet, a spherical magnet was inserted into the stem after separating the humeral head component from the stem, followed by fixation of the head component (Fig. 5). All biomechanical tests were carried out in the pre-inserted state of the coin-shaped magnet before performing the scapular position. Therefore, it was ensured that the scapular position was unchanged for all testing conditions.

Muscle Loading Conditions

Three muscle loading conditions were tested—“Cuff loading condition”: supraspinatus 10 N, subscapularis 10 N, and infraspinatus + teres minor 10 N; “Balanced loading condition”: deltoid 40 N, supraspinatus 10 N, subscapularis 10 N, infraspinatus + teres minor 10 N, pectoralis major 20 N, and latissimus dorsi 20 N; and “Unbalanced loading condition”: deltoid 40 N, supraspinatus 10 N, subscapularis 10 N, and infraspinatus + teres minor 10 N.

In the cuff loading condition, loading was applied only to the rotator cuff muscles to focus on whether the magnet could act as a substitute for the rotator cuff’s function of stabilizing the shoulder joint. For the balanced loading condition, force couples were balanced for the humeral head to be placed at the center of the glenoid. The muscle forces were determined based on the physiologic

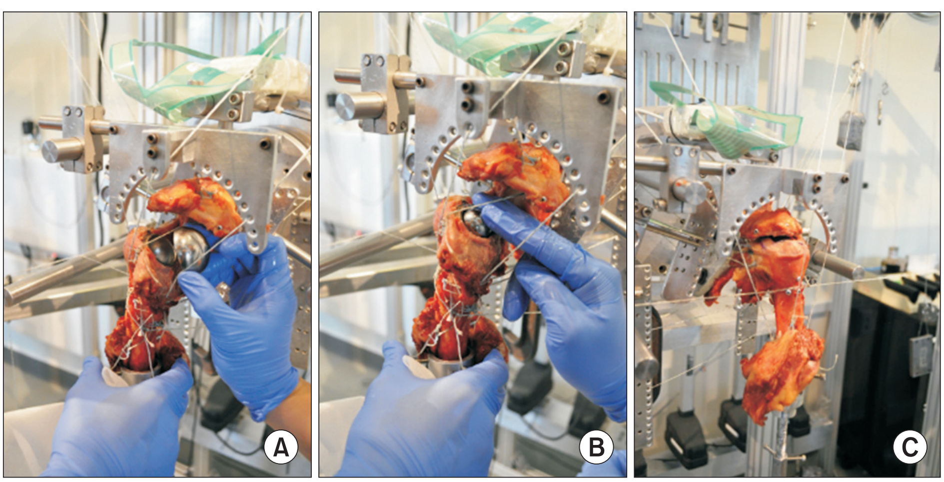


Fig. 5. Insertion of a spherical magnet. (A, B) Separation of the head component from the humeral stem and placement of the magnet. (C) Application of muscle loading after fixing the spherical magnet on the humeral stem.

cross-sectional area ratios and electromyographical studies.[11,19,20] The loading of latissimus dorsi and pectoralis major were removed during the unbalanced condition to simulate the presence of a superior load on the humeral head.

Measurements

All the measurements were made at 0°, 30°, and 60° angles of the glenohumeral abduction. In the cuff loading condition, anterior-posterior (AP) translation was measured by fixing the humeral external rotation (ER) at 30°. Before measuring the AP translations, the capsule was preconditioned with five cycles of muscle loading (15 N) in the anterior and posterior directions. Independent external translation force was applied in AP axis. The AP translations were measured in all testing conditions after applying 2.5 N–15 N (2.5 N increment in each condition) of translational forces in each direction. The superior translation was measured with ER fixed at 30º. The superior translation was preconditioned in the superior and inferior directions with 30 N muscle load. Superior translation of the humerus was measured from 5 N–30 N loads on the deltoid (5 N increment in each condition).

The location of the humeral head and superior migration were measured using a 3D digitizing system (MicroScribe 3DLX, Revware, Raleigh, NC, USA; accuracy, 0.3 mm) while performing ER of the humerus head at 0°, 30°, 60°, and 90° abduction angles. Before testing at each step, all the muscles were loaded, and the specimen was preconditioned with five cycles of muscle loading. To reduce the effect of soft-tissue viscoelasticity, specimens were taken from the position of maximum internal rotation to that of the maximum ER. Superior migration was calculated by measuring the difference in the humeral head position between the balanced loading and unbalanced loading conditions.

Subacromial contact pressures were measured using a Tekscan pressure sensor (saturation pressure, 10.3 MPa; model 4000, Tekscan, Boston, MA, USA) during loading condition 2. After placing the sensor in the subacromial space, the contact area, contact force, and peak pressure were measured at each position while externally rotating the humerus at 0°, 30°, 60°, and 90° abduction angles. Contact pressure was calculated by dividing the contact force by the contact area. The sensor's sensitivity was either set to 35 or 40 and calibrated using a 2-point calibration protocol with applied forces of 20 N and 40 N or 10 N and 30 N, respectively, using an Instron 4411 load cell (Instron, Norwood, MA, USA). A sensitivity of 40 was used for the intact condition, and a sensitivity of 35 was used for other conditions because more than four pixels were saturated.

The abduction capability of testing conditions 2 (MRCT) and 3 (MRCT with magnet) was compared. The humerus was inserted into the parallel arc guide such that

Table 1. Anterior-Posterior Translation

Measurement position	2.5 N	5 N	7.5 N	10 N	12.5 N	15 N
0° Abduction (mm)						
Intact	0.5 ± 0.2 (100)	0.8 ± 0.2 (100)	1.5 ± 0.5 (100)	2.3 ± 1.2 (100)	3.7 ± 2.4 (100)	1.9 (100)
MRCT	3.7 ± 2.6 (740)	3.6 ± 1.4 (450)	6.4 ± 2.0 (427)	8.4 ± 4.2 (365)	12.4 ± 5.1 (335)	11.4 (600)
MRCT with magnet	0.4 ± 0.1 (80)	0.8 ± 0.2 (100)	1.7 ± 0.6 (113)	2.5 ± 1.2 (109)	5.6 ± 2.5 (151)	8.0 (421)
30° Abduction (mm)						
Intact	0.3 ± 0.1 (100)	1.3 ± 0.5 (100)	4.0 ± 2.2 (100)	5.1 ± 2.5 (100)	9.3 ± 3.3 (100)	17.2 (100)
MRCT	3.4 ± 2.1 (1,133)	7.5 ± 2.3 (577)*	10.4 ± 3.1 (260)	12.2 ± 3.2 (244)*	20.0 ± 3.4 (215)	29.0 (169)
MRCT with magnet	0.4 ± 0.1 (133)	2.1 ± 1.4 (162)†	5.4 ± 3.8 (135)	6.2 ± 3.9 (124)	13.3 ± 5.3 (143)	25.2 (147)
60° Abduction (mm)						
Intact	0.5 ± 0.1 (100)	1.3 ± 0.5 (100)	2.8 ± 1.1 (100)	3.5 ± 1.4 (100)	4.9 ± 2.2 (100)	6.0 ± 2.5 (100)
MRCT	1.9 ± 0.8 (380)	3.8 ± 1.3 (292)	9.6 ± 2.4 (343)	9.2 ± 2.2 (263)	11.0 ± 3.3 (224)	14.8 ± 5.3 (247)
MRCT with magnet	0.6 ± 0.2 (120)	1.8 ± 1.1 (138)†	3.3 ± 1.9 (118)	4.4 ± 2.3 (126)	6.9 ± 2.9 (141)	8.5 ± 3.1 (142)

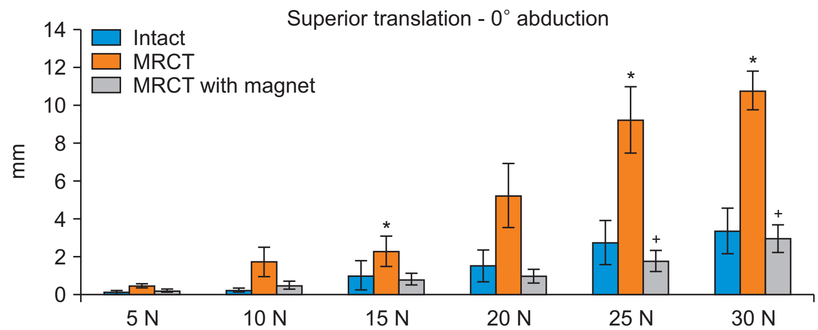
Values are presented as mean ± standard error (%).
MRCT: massive rotator cuff tear.
*Statistically significant difference compared with intact condition ($p < 0.05$). †Statistically significant difference compared with MRCT condition ($p < 0.05$).

it could freely abduct in the scapular plane. The initial position of abduction was set to 10°, with 0° humeral axial rotation. During rotator cuff muscle loading with 10 N anterior deltoid and 10 N posterior deltoid, the middle deltoid was incrementally increased from 5 N–20 N (2.5 N increment in each), and the corresponding abduction angle was recorded using MicroScribe 3DLX. To ensure repeatability, two trials were performed for each measurement.

Statistical Analysis

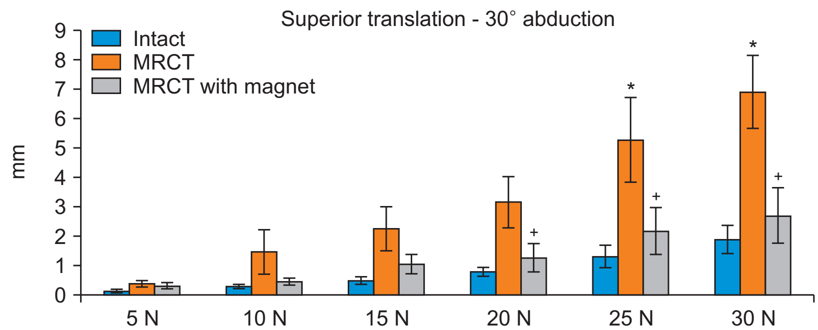
The stability and contact characteristics were analyzed using repeated measures of analysis of variance (for pairwise comparisons). Bonferroni correction was used for multiple comparisons. A $p < 0.05$ was considered statistically significant (IBM SPSS ver. 25; IBM Corp., Armonk, NY, USA). To compare the abduction capabilities, a matched pair t-test was used with $p < 0.05$ as the level for statistical significance.

A



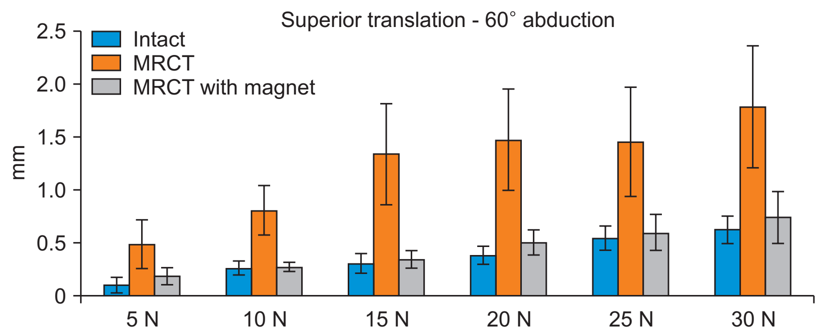
	5 N mm	5 N %	10 N mm	10 N %	15 N mm	15 N %	20 N mm	20 N %	25 N mm	25 N %	30 N mm	30 N %
Intact	0.1 ± 0.1	100	0.2 ± 0.1	100	1.0 ± 0.8	100	1.5 ± 0.8	100	2.7 ± 1.2	100	3.3 ± 1.2	100
MRCT	0.4 ± 0.1	400	1.7 ± 0.8	850	2.3 ± 0.8*	230	5.2 ± 1.7	347	9.2 ± 10.8*	341	10.8 ± 1.0*	327
MRCT with magnet	0.2 ± 0.1	200	0.5 ± 0.2	250	0.8 ± 0.3	80	1.0 ± 0.4	67	1.0 ± 0.6†	67	2.9 ± 0.7†	88

B



	5 N mm	5 N %	10 N mm	10 N %	15 N mm	15 N %	20 N mm	20 N %	25 N mm	25 N %	30 N mm	30 N %
Intact	0.1 ± 0.1	100	0.3 ± 0.1	100	0.5 ± 0.1	100	0.8 ± 0.2	100	1.3 ± 0.4	100	1.9 ± 0.5	100
MRCT	0.4 ± 0.1	400	1.5 ± 0.8	500	2.2 ± 0.8	440	3.2 ± 0.9	400	5.3 ± 1.4*	408	6.9 ± 1.2*	363
MRCT with magnet	0.3 ± 0.1	300	0.4 ± 0.1	133	1.0 ± 0.3	200	1.3 ± 0.5†	163	2.2 ± 0.8†	169	2.7 ± 0.9†	142

C



	5 N mm	5 N %	10 N mm	10 N %	15 N mm	15 N %	20 N mm	20 N %	25 N mm	25 N %	30 N mm	30 N %
Intact	0.1 ± 0.1	100	0.3 ± 0.1	100	0.3 ± 0.1	100	0.4 ± 0.1	100	0.5 ± 0.1	100	0.6 ± 0.1	100
MRCT	0.5 ± 0.2	500	0.8 ± 0.2	267	1.3 ± 0.5	433	1.5 ± 0.5	375	1.5 ± 0.5	300	1.8 ± 0.6	300
MRCT with magnet	0.2 ± 0.1	200	0.3 ± 0.0	100	0.3 ± 0.1	100	0.5 ± 0.1	125	0.6 ± 0.2	120	0.7 ± 0.2	117

Fig. 6. Superior translation (mm) measured by loading the deltoid from 0 N to 30 N in 5 N increments in the cuff loading condition. (A) 0° Abduction. (B) 30° Abduction. (C) 60° Abduction. *Statistically significant difference observed compared with the intact condition ($p < 0.05$). †Statistically significant difference compared with the massive rotator cuff tear (MRCT) condition ($p < 0.05$).

RESULTS

AP Translation

The AP translation increased in the presence of MRCTs; however, it decreased compared to condition 2 (MRCT) when the magnet was applied (condition 3). When 5 N and 10 N muscle loads were applied at 30° abduction, AP translation showed significant differences between conditions 1 (intact) and 2 (MRCT) ($p < 0.05$). Furthermore, when 5 N was applied at both 30° and 60° abduction, there were significant differences between conditions 2 (MRCT) and 3 (MRCT with magnet) ($p < 0.05$) (Table 1).

Superior Translation

Similar to AP translation, superior translation also increased in MRCTs (condition 2) and decreased when the magnet was applied (condition 3). Superior translation significantly increased after MRCTs (condition 2), which was induced by applying 15 N, 25 N, and 30 N muscle loads at 0° abduction and 25 N and 30 N loads at 30° abduction ($p < 0.05$). After inserting the magnet in condition 3 (MRCT with magnet), superior translation significantly decreased with 25 N and 30 N loads at 0° abduction and 20 N, 25 N, and 30 N loads at 30° abduction ($p < 0.05$). Superior translations in condition 3 (MRCT with magnet) were not significantly different from those in condition 1 (intact) (Fig. 6).

Superior Migration

At both 0° and 30° abduction in all the ER angles and under superiorly directed unbalanced loading, the superior migration in condition 2 (with MRCT) significantly increased, compared with the intact condition ($p < 0.05$). After the magnet was applied (condition 3), superior migration tended to decrease, as compared with condition 2 (MRCT). However, there were significant differences between the superior migrations of conditions 1 (intact) and 3 (MRCT with magnet) at 0° abduction for all the ER angles ($p < 0.05$) (Table 2).

Subacromial Contact Pressure

When superiorly directed loading was applied, the subacromial contact pressure increased significantly in condition 2 (MRCT), compared with the intact condition at 0° abduction with 30°, 60°, and 90° ER ($p < 0.05$). However, even when the magnet was applied (condition 3), there was a statistically significant difference in the contact pressure, compared with that in the intact condition at 0° abduction with 60° and 90° ER ($p < 0.05$). However, the subacromial contact pressure in condition 3 (MRCT with magnet) decreased, compared with condition 2 (MRCT). Specifically, it was significantly lower than that in condition 2 (MRCT) at 30° abduction with 60° ER ($p < 0.05$) (Table 3).

Table 2. Superior Migration

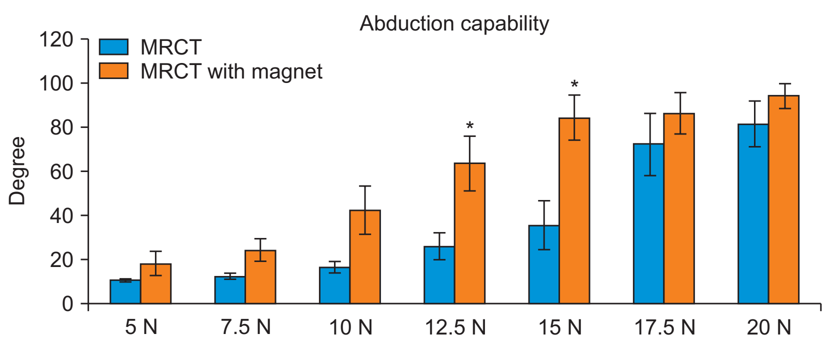
Measurement position	0° ER	30° ER	60° ER	90° ER
0° Abduction (mm)				
Intact	1.7 ± 0.5 (100)	2.7 ± 0.7 (100)	2.7 ± 0.7 (100)	2.8 ± 0.8 (100)
MRCT	6.6 ± 1.1 (388)*	9.4 ± 0.8 (348)*	9.6 ± 0.9 (356)*	10.2 ± 1.1 (364)*
MRCT with magnet	5.3 ± 0.9 (312)*	8.7 ± 1.0 (322)*	9.0 ± 1.0 (333)*	9.9 ± 1.2 (354)*
30° Abduction (mm)				
Intact	1.5 ± 0.5 (100)	1.4 ± 0.4 (100)	1.7 ± 0.6 (100)	2.2 ± 0.5 (100)
MRCT	4.8 ± 0.7 (320)*	6.1 ± 1.2 (435)*	5.7 ± 1.2 (335)*	6.0 ± 1.2 (273)*
MRCT with magnet	3.1 ± 1.0 (207)	4.3 ± 1.2 (307)	3.7 ± 1.0 (218)	3.8 ± 1.1 (173)
60° Abduction (mm)				
Intact	0.1 ± 0.2 (100)	0.2 ± 0.1 (100)	0.2 ± 0.1 (100)	0.7 ± 0.4 (100)
MRCT	0.4 ± 0.1 (400)	0.6 ± 0.6 (300)	0.8 ± 0.8 (400)	1.3 ± 1.1 (186)
MRCT with magnet	0.2 ± 0.3 (200)	0.3 ± 0.2 (150)	0.2 ± 0.1 (100)	0.3 ± 0.3 (43)

Values are presented as mean ± standard error (%).
ER: external rotation, MRCT: massive rotator cuff tear.
*Statistically significant difference compared with intact condition ($p < 0.05$).

Table 3. Mean Subacromial Contact Pressure with Unbalanced Load

Measurement position	0° ER	30° ER	60° ER	90° ER
0° Abduction (kPa)				
Intact	25.7 ± 9.9 (100)	24.7 ± 9.2 (100)	22.9 ± 10.1 (100)	6.2 ± 3.1 (100)
MRCT	31.5 ± 15.9 (126)	117.2 ± 20.9 (474)*	141.4 ± 21.2 (617)*	164.6 ± 24.9 (2,655)*
MRCT with magnet	16.8 ± 11.1 (65)	90.8 ± 26.6 (368)	116.0 ± 19.9 (507)*	132.3 ± 19.3 (2,134)*
30° Abduction (kPa)				
Intact	60.9 ± 6.4 (100)	67.0 ± 15.7 (100)	53.8 ± 10.5 (100)	26.9 ± 21.8 (100)
MRCT	90.5 ± 17.5 (149)	131.1 ± 17.4 (196)	105.6 ± 25.0 (196)	78.4 ± 19.5 (291)
MRCT with magnet	69.0 ± 15.9 (113)	90.8 ± 16.2 (136)	64.3 ± 27.5 (120)†	45.3 ± 13.3 (168)
60° Abduction (kPa)				
Intact	125.5 ± 26.4 (100)	144.1 ± 23.1 (100)	142.3 ± 39.7 (100)	60.4 ± 26.3 (100)
MRCT	147.1 ± 32.9 (117)	193.4 ± 23.2 (134)	169.4 ± 43.7 (119)	72.2 ± 26.4 (120)
MRCT with magnet	129.4 ± 26.1 (103)	202.8 ± 10.2 (141)	179.6 ± 46.7 (126)	85.9 ± 28.0 (142)

Values are presented as mean ± standard error (%).
ER: external rotation, MRCT: massive rotator cuff tear.
*Statistically significant difference compared with intact condition ($p < 0.05$). †Statistically significant difference compared with MRCT condition ($p < 0.05$).



	5 N	7.5 N	10 N	12.5 N	15 N	17.5 N	20 N
MRCT	10.7 ± 0.7	12.5 ± 1.3	16.6 ± 2.6	26.1 ± 6.0	35.8 ± 11.1	72.4 ± 14.5	81.7 ± 10.4
MRCT with magnet	18.2 ± 5.5	24.3 ± 5.2	42.3 ± 11.1	63.7 ± 12.4*	84.4 ± 10.1*	86.4 ± 9.2	94.5 ± 5.6

Fig. 7. Abduction capability (°) measured at a possible abduction angle according to the deltoid force in massive rotator cuff tear (MRCT) and MRCT with a magnet. *Statistically significant difference observed compared with the MRCT condition ($p < 0.05$).

Abduction Capability

In the testing conditions 2 (MRCT) and 3 (MRCT with magnet), the abduction angle increased with the increase in loading on the middle deltoid. The abduction angle in condition 3 (MRCT with magnet) was larger than that in condition 2 (MRCT) for every deltoid loading. When a load of 12.5 N and 15 N was applied to the middle deltoid, there were significant differences between the two groups ($p < 0.05$) (Fig. 7).

DISCUSSION

This biomechanical cadaveric study demonstrated that magnets could play a positive role as a stabilizer in decreasing the AP and superior translations in MRCTs under cuff-loading conditions. Furthermore, the contact pressure in MRCT with the magnet condition (condition 3) was significantly lower than that in MRCT (condition 2) at 30° abduction in 60° ER. Although there were significant differences between the superior migrations of conditions 1 (intact) and 3 (MRCT with magnet) at 0° abduction, the magnetic force tended to decrease the superior migration and subacromial contact pressure in MRCTs. The results of this study also showed that the magnet could facilitate abduction with less deltoid force in MRCTs.

The rotator cuff muscles provide stability to the glenohumeral joint by creating a force that compresses the humeral head into the glenoid.[2)] However, disruption of the rotator cuff muscle compromises the concavity compression force, which leads to superior migration of the humeral head and loss of stability.[2,3] A magnet can stabilize two separate entities by generating an attraction force.[16] Moreover, among various types of magnets, the ball joint magnet can maintain two objects in a constant position while allowing them to move in all directions using an attractive force.[21] This study confirmed that AP and superior translations in the cuff loading condition were increased in condition 2 (MRCT) when compared to that in condition 1 (intact). However, AP and superior translations in condition 3 (MRCT with magnet) showed results similar to those in condition 1 (intact), with no significant difference between them. We found that AP and superior translations were reduced when the magnet was applied (condition 3), as compared with condition 2 (MRCT). These results suggest that the attraction force of the magnet can at least partially replace the compressive force of the rotator cuff and eventually serve as a stabilizer of the shoulder joint in MRCTs.

MRCTs can significantly reduce glenohumeral stability and thereby cause severe functional loss of the shoulder joint, such as pseudoparalysis.[13] SCR recently gained prominence as a treatment option for irreparable MRCTs, which enables normal kinematics and effectively helps raise the arm again by providing superior stability to the glenohumeral joint.[13,22] These advantages of SCR have been verified by numerous studies reporting satisfactory outcomes, including the elimination of pseudoparalysis and functional recovery of the shoulder joint.[13,15] The current biomechanical study confirmed that the abduction angles were larger in condition 3 (MRCT with magnet) with less deltoid loading, as compared to those in condition 2 (MRCT). This observation suggests that the magnetic force inhibited humeral head elevation from the upward force of the deltoid muscle and helped maintain the CoR, thereby making it easier for the humerus to abduct. In addition, if the glenohumeral joint stability can be restored using the magnetic force, it would be possible to elevate the arm more effectively and restore the shoulder joint function, as confirmed by SCR.

To date, RTSA has been the most promising treatment strategy for restoring active arm elevation in patients with MRCT, especially with arthritic changes.[5,6] However, several complications, including the limitation of external or internal rotation, scapular notching, and acromial fractures, inevitably accompany the cost of altering the non-anatomic biomechanics chosen to elevate the arm again.[8,9,23] Our study results showed a significant improvement of the abduction capability in condition 3 (MRCT with magnet) than in condition 2 (MRCT), even with less deltoid loading. Based on these results, if it were possible to restore active arm elevation even with anatomic shoulder arthroplasty using magnets while maintaining normal biomechanics of the shoulder joint, it may be possible to achieve a wider range of motion and overcome the other drawbacks of RTSA. In the future, further comparative study of the abduction capability between anatomic shoulder arthroplasty with magnets and RTSA will be necessary to confirm whether anatomic shoulder arthroplasty using magnets can improve active elevation as much as RTSA in MRCTs.

The superior migration in condition 3 (MRCT with magnet) was significantly increased compared to condition 1 (intact) at 0° abduction, although the magnetic force tended to decrease overall superior migration in MRCTs. This result may have been influenced by two different reasons. First, the strength of the magnet used in this study was insufficient to endure the deltoid force with superiorly directed unbalanced loading. Since magnetic force obeys an inverse square law with distance, placing two magnets closer to each other will create a stronger force.[17] Therefore, using a spherical magnet with a larger diameter in the humerus or moving the magnet in the glenoid closer to the humerus can be inferred as a countermeasure, which should be verified in further studies. Second, the absence of a spacer is considered another potential reason. In fact, the strength of the magnet, which should serve as a substitute for the rotator cuff muscles in MRCTs, may not have to be strong enough to overcome the unbalanced deltoid force. Numerous biomechanical studies have reported that SCR decreases superior migration in superiorly directed unbalanced loading.[11,24] One of the working mechanisms of SCR is the spacer effect, and the graft acts as a spacer to compress the humeral head against the acromion.[25] Mihata et al.[24] reported that the graft of fascia lata with 8 mm thickness could provide greater shoulder stability than that of a graft with 4 mm thickness. The difference in shoulder stability provided by grafts with different thicknesses revealed that the graft functions as a spacer.[25] The recent *in vivo* study by Kane et al.[26] also reported that SCR did not depress the humeral head and had minimal effect on glenohumeral kinematics and that the graft might simply act as a subacromial spacer. Moreover, Singh et al.[27] demonstrated that a subacromial balloon spacer could provide the same mechanical effect that depresses superior humeral head migration similar to that of SCR. Based on these observations, the absence of a spacer can be considered as one of the reasons for the inability of the magnet to sufficiently inhibit superior migration when a direct superior unbalanced load was applied, compared with that of the intact condition. Therefore, it would be necessary to explore solutions to problems that are caused by the absence of a spacer.

Although some positive results for stabilizing the shoulder joint using the magnet were found in this study, it is uncertain how the magnets will affect the human body. For example, there is a possibility that wear particles may occur due to the pulling force of the magnet. Since it is uncertain how these particles will affect the human body or how they will interact with magnets, this might be a potential complication that should be solved for the clinical application of magnets in the shoulder joint. However, magnets are reported to be relatively safe for the human body, and there has been a steady increase in the usage of magnets in medical devices and surgical techniques.[28,29)] For instance, magnets have already been used in orthodontic operations, and magnetic intramedullary compression nails have been developed and reported to be effective for severe nonunion cases.[28,29)] Furthermore, Doursounian et al.[30)] reported a case in which magnetic shoulder arthroplasty was performed as a tumor prosthesis, although it was different from the concept devised in this study. Nevertheless, it is still unclear how a magnet inserted into the human body affects health, and additional studies that can prove its safety for the human body are essential.

This study has several limitations. First, this study provides only time zero information, which is an inherent limitation of all cadaveric studies. The dynamic movements of the shoulder joint, such as active muscle contraction, interactions between muscles, and proprioceptive control cannot be assessed in cadavers. Second, as the results derived from this study are from a cadaver, it is difficult to apply them in clinical practice yet. Third, we used head components of the same size to maintain a constant magnetic effect for each cadaver shoulder. Therefore, the influence of the head component size on shoulder joint stability was not considered. Finally, this study was a cadaveric pilot study to prove the concept that the magnets could stabilize the shoulder joint, and the magnet on the glenoid side was simply inserted. For clinical application, the technical concerns about safely and firmly positioning the magnet will have to be resolved. Despite these limitations, the strength of this study is that it is the first biomechanical research that confirmed how magnets could affect the stability of the shoulder joint. We believe that this study provides valuable information to clinicians and researchers as a source of new ideas and trials for future treatments.

In conclusion, the magnet biomechanically played a positive role in stabilizing the shoulder joint and enabled abduction with less deltoid force in MRCTs. This study is meaningful in that it is the first study to investigate whether magnets could contribute to shoulder joint stabilization. However, to ensure that the magnet is clinically applicable as a stabilizer for the shoulder joint, it is necessary to thoroughly verify its safety in the human body and to conduct further research on technical challenges, such as appropriate magnet strength and complement for the subacromial spacer.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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