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An in-vitro biomechanical comparison of annular ligament repair and reconstructions to restore radial head stability in anterior Monteggia fractures

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Background: Persistent or recurrent instability of the radial head (RH) remains a challenge in treating anterior Monteggia fractures despite anatomic restoration of the ulna. RH instability may be caused by the pull of the biceps muscle with rupture of the annular ligament and other soft tissue stabilizers of the proximal radius. Currently, the optimal method to stabilize the proximal radius is unknown. The purpose of this study was to compare annular ligament repair with three different ligament reconstructions in restoring anterior RH stability.
Methods: Eight cadaveric upper extremities were mounted on an elbow simulator in 90 degrees of flexion with the forearm in neutral rotation. Simulated sequential biceps loading was applied in 10 N increments up to a maximum biceps load of 150 N to generate an anteriorly directed force to the RH. Testing was first conducted in the native state with all soft tissue intact, followed by sectioning the central interosseous membrane, the proximal interosseous membrane, and annular and quadrate ligaments. This was followed by the randomized evaluation of an annular ligament repair and three different ligament reconstructions, including a Bell Tawse reconstruction with triceps fascia (Bell Tawse reconstruction), a free tendon annular ligament reconstruction (Itadera reconstruction), and a free tendon anatomic annular ligament reconstruction (anatomic reconstruction). An optical tracking system was used to determine RH kinematics relative to the humerus. For all test states, the anterior translation of the RH relative to the capitellum was quantified as a measure of subluxation.
Results: Sectioning the soft tissue stabilizers of the proximal radius produced a significant increase in anterior RH subluxation relative to the intact state ($P < .001$). The annular ligament repair was most effective at reducing anterior radial subluxation ($P = 1.000$). The Itadera reconstruction was the next most effective procedure at reducing anterior RH subluxation ($P = 1.000$) and was followed by the anatomic reconstruction ($P = .192$) and the Bell Tawse reconstructions ($P = .015$), respectively.
Conclusion: Annular ligament repair was most effective in restoring normal RH stability; however, repair of this structure may not always be feasible as the tissues are often compromised by the injury and may not be reparable. The Itadera reconstruction was the most effective reconstruction technique at restoring RH stability and should be considered over alternative procedures when annular ligament repair is not feasible. These data also suggest that careful rehabilitation will be important postoperatively as residual RH instability can occur even with an anatomic reduction of the ulna and annular ligament repair or reconstruction.

Monteggia fractures are complex orthopedic injuries characterized by a fracture of the proximal ulna along with dislocation of the radial head (RH).[25] The outcomes of Monteggia injuries are quite variable and often suboptimal, particularly in the adult population.[14,16] Persistent and recurrent subluxation and dislocation of the RH can occur and lead to poor outcomes, even in the setting of an

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anatomical reduction of the ulna.[4,6,18] This results in pain, stiffness, weakness, and functional disability.[4,6] Activation of the biceps pulls the RH anteriorly and contributes to persistent instability due to the disruption of the stabilizing structures of the proximal radius.[1] RH instability can also occur in isolated RH dislocations; however, these are much less common than Monteggia injuries.[5,10,24]

Given that in many cases of anterior Monteggia injuries there is an inability to repair the native annular ligament, various methods of annular ligament reconstruction have been developed to address persistent radiocapitellar instability.[21,33] One technique reported by Bell Tawse involved the use of a triceps brachii tendon strip.[3] Lloyd-Roberts et al[19] modified this approach using the lateral triceps tendon bundle, in addition to proposing a separate technique utilizing the palmaris longus (PL) tendon for stabilization. Modern techniques, such as those proposed by Itadera et al,[13] use a PL tendon autograft, passing it around the radial neck via a bony tunnel created in the ulna. Nwoko et al[23] recommended the use of the brachialis muscle's superficial head for reconstruction due to its optimal location and graft availability. Recently, Marinello et al[21] offered a modified Bell Tawse technique involving a completely detached lateral triceps tendon strip and suture anchors in full forearm supination to reduce the radio-capitellar joint. They also proposed incorporating remnants of the native annular ligament for added reinforcement.

Although various surgical procedures have been proposed for the reconstruction of chronic Monteggia injuries, poor long-term outcomes with high complication rates have been reported, with no commonly agreed upon reconstruction technique for optimal treatment. Bony corrections such as dorsal overcorrection of the ulna have also been described to help stabilize the RH; however, the focus of this study was on soft tissue alternatives.[11,15,20] In light of the foregoing, the aim of this study was to compare an annular ligament repair with three different annular ligament reconstructions in their ability to restore native RH stability in an anterior Monteggia fracture cadaveric model. The three reconstructions evaluated in this study included the following: (1) a Bell Tawse reconstruction, (2) a free tendon graft reconstruction described by Itadera et al, and (3) a new, more proximally located, free tendon graft reconstruction termed the anatomic reconstruction. We hypothesized that repairing the annular ligament would be most effective in restoring normal anterior RH stability and that the anatomic reconstruction would restore optimal stability.

Materials and methods

Specimen preparation

Eight fresh-frozen cadaveric right upper extremities (mean age: 73 ± 18 years) were obtained for the biomechanical evaluation. All cadavers were scanned using computer tomography to ensure there were no signs of articular pathology or skeletal deformity. Prior to testing, each cadaver was resected at the mid-diaphysis of the humerus and thawed at room temperature (~22°C) for a minimum of 18 hours. Using a Henry approach and posterior approach to the elbow, respectively, the distal tendons of the biceps and triceps were tagged using #5 Ethibond (Ethicon, Johnson & Johnson, New Brunswick, NJ) in a running locking fashion. Optical tracking markers were rigidly fixed to the radius, ulna and humerus with 2 bicortical screws each to quantify the position and orientation of each bone throughout testing.

Experimental setup and loading protocol

A previously validated elbow simulator was used to conduct all biomechanical testing (Fig. 1).[7,8,29] For each cadaver, the humerus was fixed to the simulator using two threaded clamps while a floor mount was used to position the elbow in 90 degrees of flexion and the forearm in neutral rotation by clamping the hand in a locked position. The braided line sutured to the biceps and triceps were routed along physiological muscle lines to computer controlled pneumatic actuators. Static muscle loading was applied to the biceps and triceps using a 2:1 ratio in 10 N increments, up to a maximum biceps load of 150 N. A maximum load of 150 N was determined from several pilot studies which showed this load to be sufficient in capturing the different changes in RH translation between all test states. Antagonistic loading of the triceps was used to prevent flexion of the elbow during testing.

Repair and reconstruction protocols

The native state of each cadaver was first evaluated (intact). Dissection was then carried out through an anterior Henry approach to gain access to the anterior forearm and elbow. The anterior joint capsule was then sectioned transversely to gain access to the elbow joint for direct visualization of the annular and quadrate ligaments. Soft tissue stabilizing structures of the proximal radius were then sectioned, including the proximal interosseous membrane (IOM), central IOM, annular ligament, and quadrate ligament (Fig. 2).

An annular ligament repair and three different annular ligament reconstructions were then evaluated in a randomized order (Fig. 3). The annular ligament repair and all the reconstructions were performed using #2 Ethibond. For the Itadera reconstruction, bone tunnels were drilled in the ulna just distal to the radial notch from anterior to posterior with the exiting limb drilled from lateral to medial just beneath the supinator crest at the same level of the anterior to posterior tunnel to allow passage of the graft from anterior to lateral and around the radius. Thus, allowing the graft to then be sutured onto itself. Flexor digitorum superficialis (FDS) of digits 3 or 4 were used for tendon grafts. The anatomic reconstruction was prepared in a similar fashion to that of the Itadera reconstruction. However, bone tunnels were drilled proximal to that of the Itadera tunnels at the level of the proximal radioulnar joint, allowing for the graft to sit directly at the RH and once again be sutured onto itself. Again, FDS of digits 3 or 4 were used for tendon grafts. The final reconstruction evaluated was the Bell Tawse reconstruction, which utilized a strip of triceps fascia. To perform this procedure, the strip of triceps fascia was left attached to the ulna distally and then looped around the radial neck without bone tunnels and sutured to itself.

Kinematic analysis and outcome variables

For all testing conditions, an optical tracking system (Optotrak Certus; Northern Digital, Waterloo, ON, Canada) was used to quantify the position and orientation of the radius relative to the humerus. To quantify the position and orientation of each bone throughout testing, the optical tracking markers that were rigidly affixed to bone emitted infrared light that was detected by the camera within connected to this system.[7] From this, the position and orientation of these markers relative to a global coordinate system were then computed in real-time. These systems offer a highly precise and repeatable method at recording the position and orientation of different markers in space,[21] with a marketed accuracy of 0.1 mm. After testing was completed, the humerus and radius were denuded of all soft tissue while the optical tracker rigidly affixed to each bone was left in place. To quantify the location of several important bony landmarks on both the humerus and radius relative to their respective optical trackers, these landmarks were digitized using an optical tracking stylus

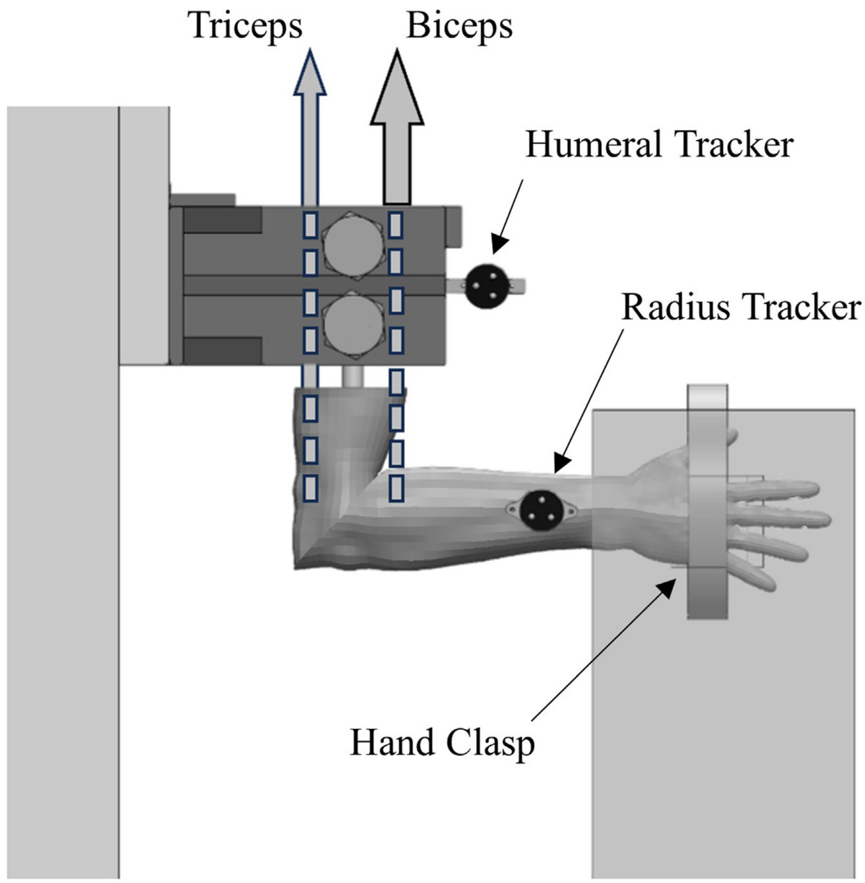

Figure 1 Right cadaveric elbow mounted onto a biomechanical simulator in 90° of flexion in neutral rotation.

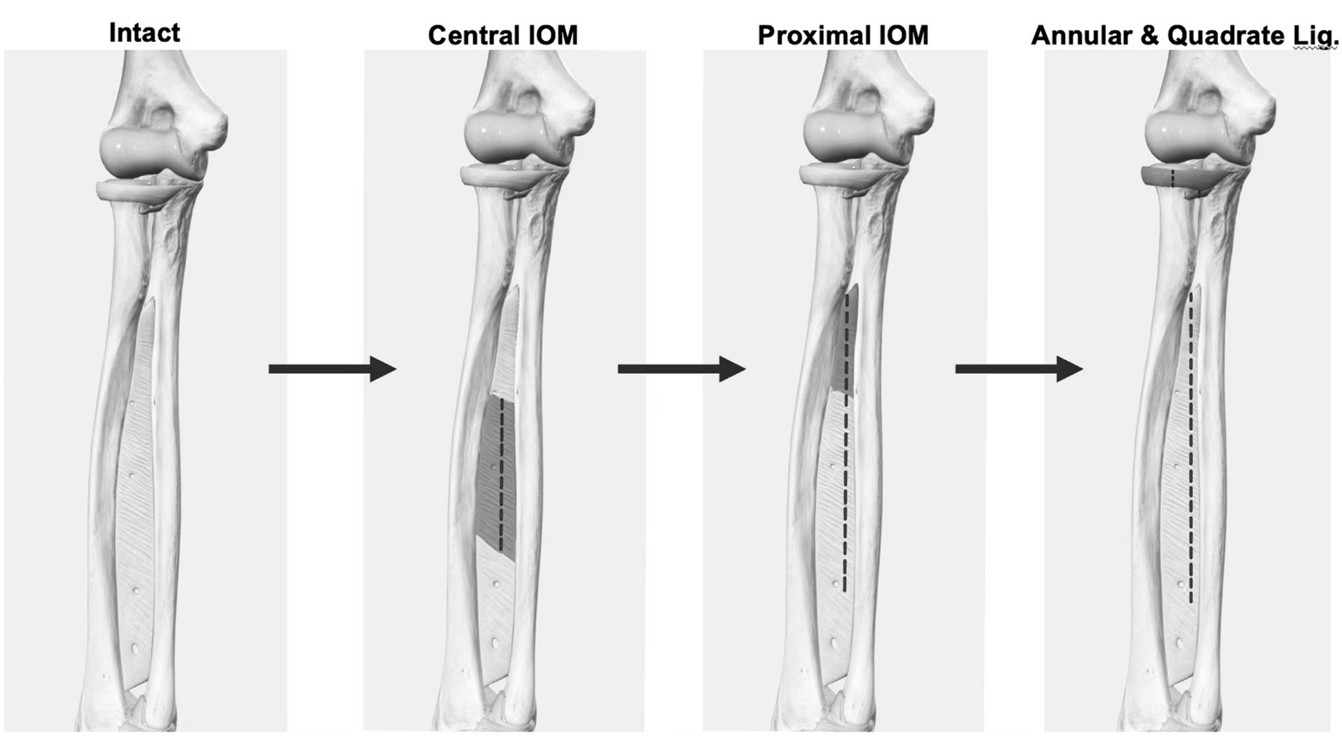

Figure 2 Soft tissue sectioning. Tissues being sectioned from left to right: intact, central IOM, proximal IOM, annular and quadrate ligaments. *IOM*, interosseous membrane

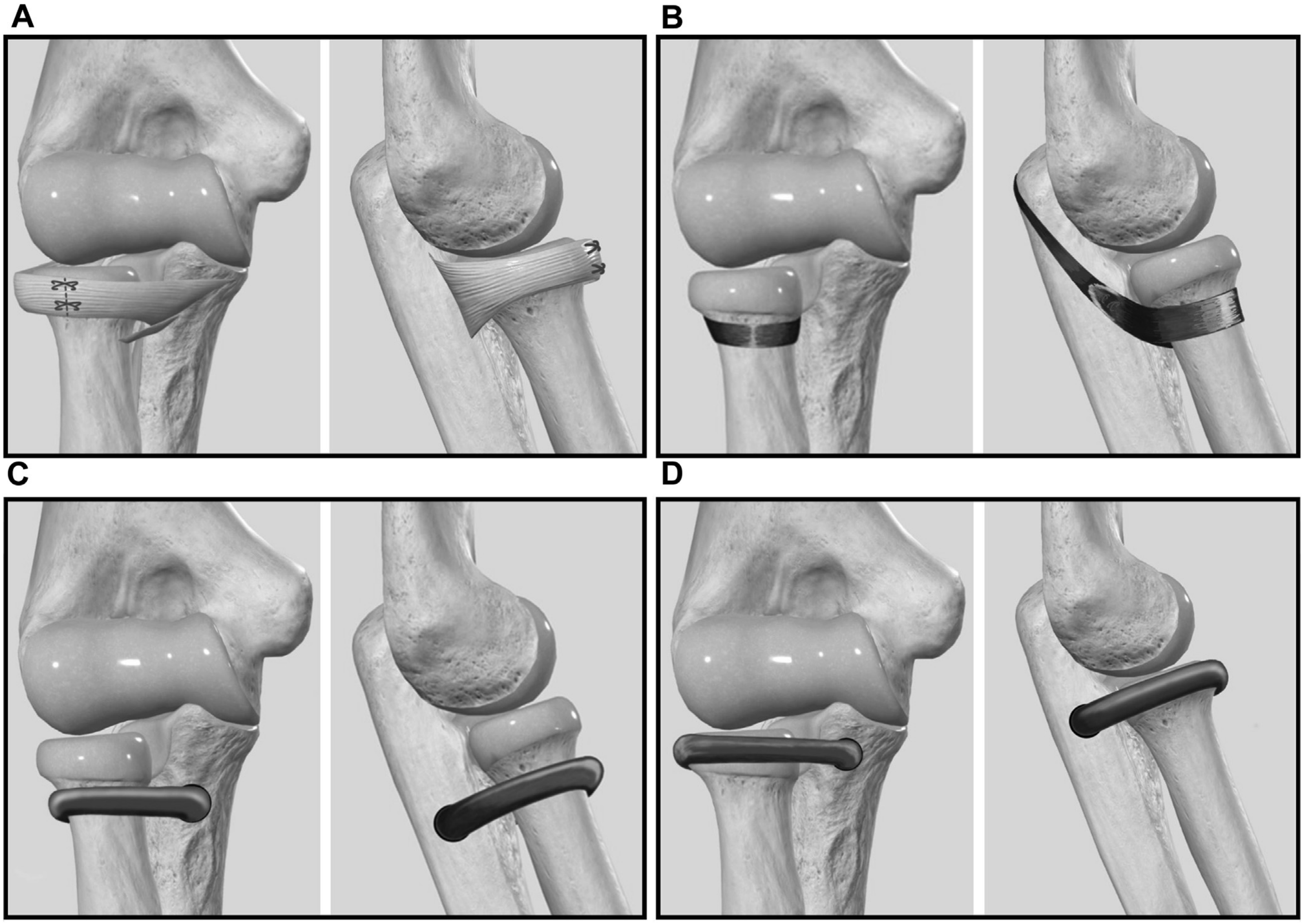

Figure 3 (**A**) Annular ligament repair, (**B**) Bell Tawse annular ligament reconstruction, (**C**) Itadera annular ligament reconstruction, and (**D**) anatomic annular ligament reconstruction. All illustrations are shown from an anterior and lateral view.

relative to the corresponding optical tracking marker on each bone. The medial and lateral epicondyles of the humerus were digitized in addition to performing a trace of the humeral shaft to develop a distal humeral coordinate system. A trace of the capitellum was performed and was used in a sphere fitting algorithm to approximate the center and diameter of the capitellum (Fig. 4). A trace of the RH rim was used to determine a plane and a vector orthogonal to said plane centered within the RH, which best fit the rim of the RH. The capitellum center and vector orthogonal to the rim of the RH were projected into the sagittal plane of the humerus coordinate system to eliminate medial or lateral translation of the RH from this analysis. Once this was complete, the length of the perpendicular bisector between the RH vector and the center of the capitellum was determined for each test state.

The length of the perpendicular bisector between the RH vector and the center of the capitellum was determined for each test state. If the RH vector passed anteriorly to the center of the capitellum, this length was taken as positive. The length of the perpendicular bisector was then divided by the diameter of the capitellum's best-fit sphere to give the radiocapitellar ratio (RCR). Positive RCR values corresponded to anterior RH subluxation while negative values corresponded to posterior RH subluxation. Furthermore, an RCR of 100% correlated to complete dislocation of the RH relative to the capitellum. This metric has previously been used to quantify anterior subluxation of the RH on two-dimensional radiographs.[26]

Based on the mean values of the RCR for each condition, a stability factor (SF) was also developed. This was determined using equation (1) below:

$$SF = \frac{100 - RCR}{100 - RCR_{Intact}} \tag{1}$$

where *RCR* corresponds to the mean RCR of the condition of interest, while RCR_{Intact} corresponds to the mean RCR of the intact condition. This equation was used to provide a simple index measure which quantified the RH stability of each condition relative to the intact soft tissue condition. Values ranged between 0 and 1, with a value of 1 representing equivalent stability relative to the intact soft tissue state.

Statistical analysis

A two-way repeated-measures analysis of variance was used to statistically compare the effect of the arm state and biceps loading magnitude on the RCR. This analysis was performed using validated software (SPSS; IBM Corp., Armonk, NY, USA) with statistical significance set to $P \leq .05$.

Results

The RCR for all elbow states are shown in Figure 5 over the full range of biceps loading. The intact soft tissue state exhibited the

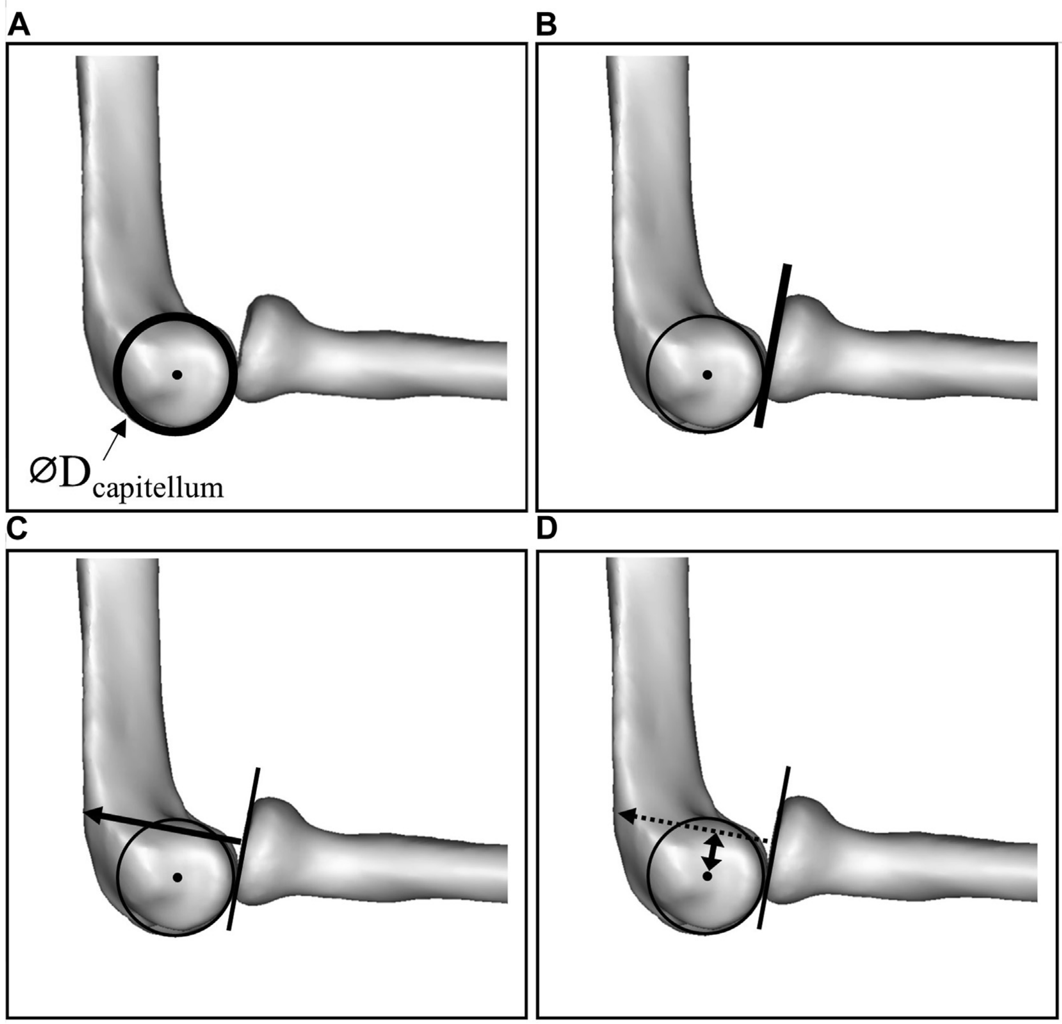

Figure 4 These illustrations show the process used to determine the radiocaptiellar ratio (RCR) for each testing condition. (**A**) A sphere-fitting algorithm is used to determine the center and diameter (φD) of the capitellum. (**B**) A best fit plane is fitted to the trace of the radial head rim and is (**C**)used to determine a vector passing through the center of the radial head. (**D**) The length of the perpendicular bisector between this vector and capitellum center is divided by the diameter of the capitellum to determine the RCR.

least amount of anterior RH subluxation with a mean RCR of 5 ± 7%. This was followed by the annular ligament repair (6 ± 11%) and Itadera reconstruction (21 ± 21%), respectively. Neither the mean RCR for the repair nor Itadera reconstruction were significantly different compared to the intact soft tissue condition ($P = 1.000$). The conditions exhibiting the greatest anterior RH subluxation included the sectioned soft tissue state (78 ± 34%), the Bell-Tawse reconstruction (69 ± 40%), and the anatomic reconstruction (60 ± 35%), respectively. All three reconstructions exhibited significantly greater RCRs compared to both the intact ($P \leq .001$) and the annular ligament repair conditions ($P \leq .002$). The Itadera reconstruction exhibited a significantly lower RCR compared to the sectioned soft tissue state and Bell Tawse reconstruction ($P \leq .005$) but was not significantly different compared to the anatomic reconstruction ($P = .12$).

Excluding the intact soft tissue state, which always resulted in a SF of 1, the annular ligament repair exhibited the greatest SF of 0.98. This was followed by the Itadera reconstruction with a SF of 0.83. Similar SF values were observed between anatomic and Bell Tawse reconstructions of 0.42 and 0.33, respectively. The lowest SF was observed in the sectioned soft tissue state with a value of 0.23.

Discussion

Persistent or recurrent instability of the RH despite anatomic reduction of the ulna continues to be a challenge in anterior Monteggia fractures.[4,9,22] Persistent RH instability is due to the pull of the biceps muscle with rupture of the annular ligament and other soft tissue stabilizers of the proximal radius.[1] Currently, the optimal method to stabilize the proximal radius and reconstruct the annular ligament is unknown. A comparison of annular ligament repair with three different annular ligament reconstructions in restoring RH stability would aid in optimizing patient outcomes.

This biomechanical investigation demonstrated significant anterior RH translation with sectioning of the soft tissue stabilizers of the RH despite maintenance of the anatomic alignment of the ulna. These findings are consistent with previous anatomic and biomechanical studies showing worsening RH subluxation with compromise to the annular ligament in the setting of Monteggia injuries.[2,28] In our study, the annular ligament repair was most effective at reducing anterior RH instability observed after sectioning the proximal soft tissue stabilizers (ie, central and proximal IOM as well as annular and quadrate ligaments). The annular ligament repair exhibited similar stability to that of the

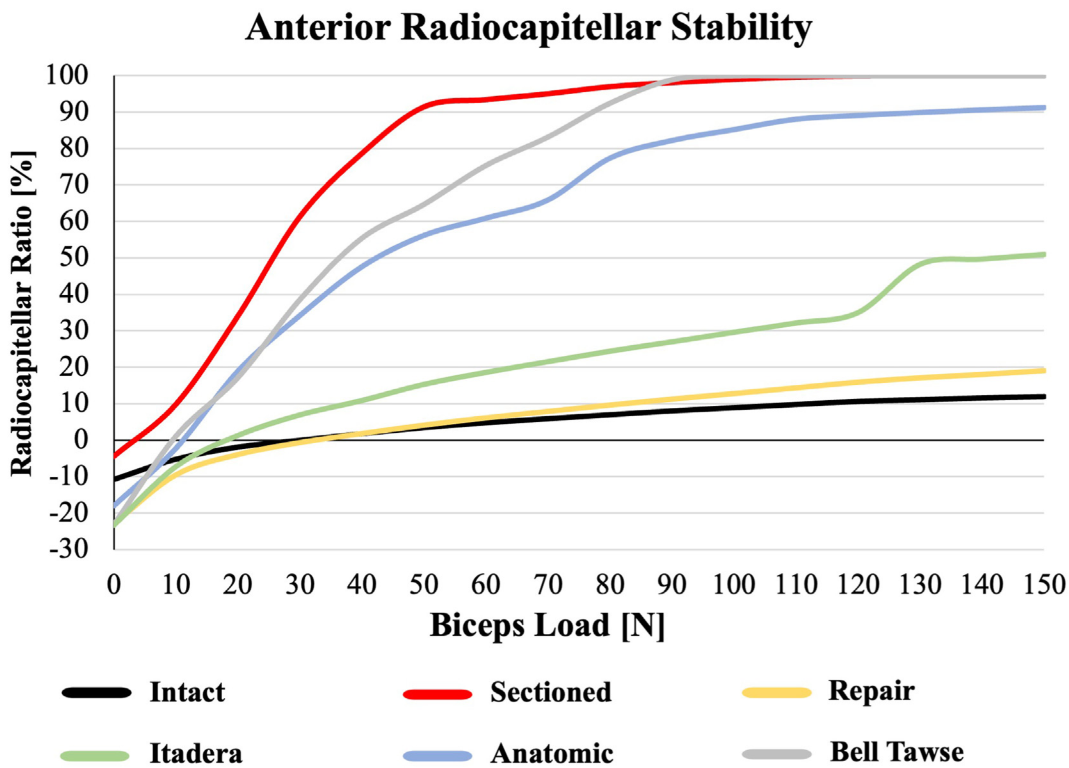

Figure 5 The mean radiocapitellar ratio is shown across the full biceps loading range for the intact and sectioned soft tissue states, annular ligament repair, and three annular ligament reconstructions. The standard deviation range for each state was as follows: intact = 19%-26%, sectioned = 0%-44%, repair = 12%-18%, Itadera = 14%-35%, anatomic = 11%-35%, and Bell Tawse = 0%-36%.

intact soft tissue state with a SF of 0.98. This was most likely due to the fact that the repair, as opposed to the other reconstructions, most accurately restored the native anatomy. However, annular ligament repair is often not possible clinically as the structural integrity of this ligament is often compromised due to the injury.[33] This requires an alternative approach to restoring RH stability using an annular ligament reconstruction.

The results from our study showed the Itadera technique to be most effective reconstruction tested in restoring RH stability, followed by the anatomic reconstruction and Bell Tawse, respectively. We believe these trends occurred due to the ability of reconstruction to mimic the function of the native annular ligament. The anatomic reconstruction, although best replicating the position of the annular ligament had a tendency to subluxate either into the radiocapitellar joint or distal to the RH. When this reconstruction subluxated off the RH its tension decreased and allowed for greater anterior RH subluxation to occur. Thus, it was unable to reliably maintain its position around the RH, allowing for more instability of the RH in comparison with the Itadera reconstruction.[13] Conversely, the Itadera reconstruction, although its location is more distal to the native annular ligament, it is able to reliably remain in its position without subluxating proximally or distally and so offered more consistent graft tensioning and hence stability of the proximal radius than the other reconstructions. Finally, although the Bell Tawse reconstruction also worked to stabilize the radius in a similar anatomical position as the Itadera reconstruction, we believe its poor performance can be attributed to the poor strength of the triceps fascia in comparison to the reconstructions using free tendon graft.[3,13] It is also important to note that the triceps facia tended to fail at its site of origin along the olecranon, whereas the tendon to tendon suture fixation in the reconstructions never failed during any of the trials.

Annular ligament repair and reconstruction also plays a crucial role in addressing isolated anterior and anteromedial dislocations of the RH.[12,31] Dislocations of the RH are usually associated with forearm fractures; however, isolated RH dislocations are rare injuries.[5,10,24] The annular ligament is a critical stabilizing structure for the RH, and is torn during isolated RH dislocations, leading to persistent pain, limited range of motion, and instability of the elbow joint.[17,27,30] Repair or reconstruction of the annular ligament is often necessary to restore stability and function to the affected joint.[31,32] Various techniques have been described, including repair of the damaged ligament or reconstruction when it cannot be adequately repaired.[3,12,13,31] This findings of this current biomechanical study likely also apply to the management of isolated RH dislocations.

The results of this biomechanical evaluation have several clinical implications. This study suggests that RH instability may persist even after anatomic restoration of the ulna in an anterior Monteggia fracture, emphasizing the importance of soft tissue stabilizers of the proximal radius and suggesting careful rehabilitation for the patient following reduction. Given our results, we would recommend annular ligament assessment and repair if possible in the acute setting.[33] In the setting of chronic instability, where annular ligament repair is not possible and a reconstruction is needed, our data supports the use of a free tendon graft reconstruction of the annular ligament as described by Itadera.[13] Clinical studies are needed to confirm the efficacy of the Itadera reconstruction.

This in-vitro biomechanical study has certain limitations. These injuries typically occur in individuals younger than the mean age of the cadavers used in this biomechanical study. The diminished soft tissue flexibility in older specimens relative to children and adolescents might lead to an underestimation of the RH instability.

Another limitation would include inadequate replication of soft tissue properties as aging and postmortem changes can alter the properties of soft tissues in cadavers, potentially reducing the relevance of the findings to live human tissues. Another limitation to consider would be graft choices. Here, FDS 3 and 4 were used and randomly assigned for either the Itadera or Anatomic reconstruction. We used these grafts as they were similar to each other in terms of thickness and length; however, it is important to note that the typical graft choice clinically would be to use PL. In comparison to FDS 3 and 4, PL seemed to be of smaller diameter, albeit marginally. However, this translation in the clinical setting is yet to be studied and does pose its own set of limitations. In addition, given the testing methodology, we were unable to test the efficacy of these repairs and reconstructions in different forearm rotations.

Another limitation of this study was that static muscle loading was employed to simulate anterior RH instability, which is a simplification of the dynamic muscle loading that occurs in-vivo. However, we believe this loading method was sufficient for illustrating the various trends in RH instability between the different repairs and reconstructions evaluated, without compromising soft tissue integrity. In addition, the range of static forces used (0-150 N) was effective at illustrating all instability trends in this study. Although the greatest subluxation for some test states was observed to occur at forces less than 100 N, a maximum force of 150 N was used to ensure all possible instability trends were captured. This force range also captured the range of muscles forces previously reported in cadaver studies.[8]

Conclusions

This biomechanical investigation demonstrates that anterior RH subluxation was observed with biceps activation when all radial soft tissues stabilizers were sectioned even with the ulna in the anatomical position. Our study demonstrated that the annular ligament repair most closely restored RH stability to that of the intact state while the Itadera technique was the most effective reconstruction.

Disclaimers:

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

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