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Posteromedial rotatory incongruity of the elbow: a computational kinematics study

Gokhan Karademir, MD[a,*], Daniel R. Bachman, MD[a], Antonis P. Stylianou, PhD[b], Akin Cil, MD[a]

[a]*Department of Orthopaedic Surgery, University of Missouri–Kansas City, Kansas City, MO, USA*
[b]*Department of Civil and Mechanical Engineering, University of Missouri–Kansas City, Kansas City, MO, USA*

Background: Our objective was to analyze the effect of different anteromedial coronoid fracture patterns with different combinations of ligamentous repairs. We hypothesized that smaller fractures would be sufficiently treated with ligamentous repair alone but that larger fragments would require a combination of ligament and bony repair versus reconstruction.
Methods: Two multibody models were created from cadaveric specimens in the ADAMS program. Four different conditions were simulated: (1) no fracture, (2) O'Driscoll anteromedial subtype I (2.5-mm) fracture, (3) subtype II 2.5-mm fracture, and (4) subtype II 5-mm fracture. In each of these conditions, 3 ligament repairs were studied: lateral ulnar collateral ligament (LUCL), posterior bundle of the medial collateral ligament (pMCL), and both LUCL and pMCL. For each condition, kinematics and articular contact areas were calculated.
Results: LUCL repair alone increases whereas pMCL repair decreases internal rotation of the ulna relative to all tested posteromedial rotatory instability conditions; their rotational effects are summative when both ligaments are repaired. With a subtype I fracture and both pMCL and LUCL injuries, repairing the LUCL alone corrects angulation whereas rotational stability is satisfactory through the arc from 0° to 90°. In a subtype II 2.5-mm fracture, isolated repair of the LUCL or pMCL is not capable of restoring rotation or angulation. For a subtype II 5-mm fracture, no combination of ligamentous repairs could restore rotation or angulation.
Conclusions: This study suggests that LUCL repair alone is sufficient to restore kinematics for small subtype I fractures for an arc avoiding deep flexion; whereas nearly normal kinematics throughout the arc of motion can be achieved if the pMCL is also repaired. Larger anteromedial coronoid fractures should ideally have fragments fixed in addition to ligament repairs.
Level of evidence: Basic Science Study; Computer Modeling

Keywords: Posteromedial rotatory incongruity of elbow; computational; multibody kinematics study; instability; anteromedial coronoid fracture; ligament; repair

This computational kinematics study was conducted under protocol number 13-635, which was approved by the University of Missouri–Kansas City Institutional Review Board on May 12, 2015.
Indicates paper was nominated for Neer Award.

*Reprint requests: Gokhan Karademir, MD, University of Missouri–Kansas City, 2401 Troost Ave, Kansas City, MO 64108, USA.
E-mail address: dr@gokhankarademir.com (G. Karademir).

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Isolated coronoid fractures are rare injuries; thus, most coronoid fractures are usually associated with ligament injuries.[1,7,20,22,29,36] O'Driscoll et al[20] classified coronoid fractures as coronoid tip, anteromedial, and basal fractures. The O'Driscoll classification further subdivided anteromedial coronoid fractures based on the extent of involvement of the anteromedial facet. Subtype I fractures involve the anteromedial rim. Subtype II fractures involve the coronoid tip and the anteromedial rim with the fracture line usually exiting the cortex in the anterior part of the sublime tubercle. Subtype III fractures completely involve the sublime tubercle and the anteromedial rim.[20]

The O'Driscoll classification outlines the injury mechanism and associated injuries. Thus, it is a helpful guideline when determining the treatment strategy. It has been stated that only patients with small anteromedial-rim coronoid fractures and minimal opening of the radiocapitellar joint on varus stress radiographs can be treated nonoperatively and the rest of the injuries need to be addressed surgically.[30]

There are 3 components of varus posteromedial rotatory instability (PMRI): anteromedial coronoid fracture, lateral ulnar collateral ligament (LUCL) injury, and posterior bundle of the medial collateral ligament (pMCL) injury.[20] Although the individual components of PMRI are well defined, there is not much agreement to direct the surgical repair of individual components.[1,22] Cadaveric studies have addressed portions of the ligamentous and bony components of this injury; however, to our knowledge, continuous rotational and angular kinematic data simultaneously addressing all 3 components leading to PMRI have not been presented in the literature.[5,7,23] Changes in elbow articular contact pressure after anteromedial coronoid fractures and LUCL injuries have been described recently.[3] Significant increases in contact pressure were shown for LUCL-deficient elbows with anteromedial coronoid fractures.[3,5] In another study, significant rotational instability without an anteromedial coronoid fracture was measured after isolated injury to the pMCL.[12] Missed or inadequately treated PMRI can lead to rapidly progressive osteoarthritis of the elbow.[3,5,20,32,37] The components of the injury pattern that can be managed without surgical intervention versus those for which surgical repair is recommended remain undefined.[12,22,30,37]

The mechanism of trauma that produces PMRI are axial loading, internal rotation of the forearm relative to the humerus, and varus force.[5] The proximal forearm pronates relative to the humerus. Typically, it leads to an LUCL deficiency and unique fracture of the anteromedial coronoid due to impaction from the humeral trochlea. Various fracture patterns of the coronoid anteromedial facet can cause elbow injuries with different kinematic characteristics.[13,22]

Our objective was to analyze the effect of various anteromedial coronoid fracture patterns with different combinations of ligamentous repairs on elbow kinematics and articular contact area in anatomic computational multibody elbow joint models. We hypothesized that smaller fracture patterns would be sufficiently treated with ligamentous repair alone but that larger fragments would require a combination of ligament and bony repair versus reconstruction of nonrepairable coronoid fractures.

Materials and methods

This is a computational kinematics study investigating the effects of different fracture patterns of the anteromedial facet of the coronoid with different combinations of ligament repair by measuring kinematic data and the contact area of the elbow affected by PMRI.

Creation of multibody models

Two multibody models created from intact cadaveric specimens were used for this study: right arm of a 61-year-old male cadaver (specimen 1) and right arm of a 42-year-old male cadaver (specimen 2). The multibody models were built in the ADAMS program (MSC Software, Santa Ana, CA, USA), which is a commercially available multibody dynamic analysis program. The multibody model creation has been previously described.[25,26] In brief, the 3-dimensional geometries of bones and cartilage were derived from computed tomography and magnetic resonance imaging (MRI) (Siemens Medical Solutions, Malvern, PA, USA). The images were obtained with a slice thickness of 1.25 mm in full extension and forearm supination. The 3D Slicer program (www.slicer.org) was used to create the geometries by using automatic threshold and manual segmentation. Cartilage geometries were determined by subtracting the computed tomography–derived bone geometries from the bone-cartilage MRI-derived geometries.[12] The geometries were post-processed in MeshLab (www.meshlab.net, open-source system), which included removing the spikes and noise and decimating the geometries to reduce the file size.[40] The geometries were then imported and aligned in ADAMS. To allow contact area calculation, the humeral cartilage was modeled as 5 × 5–mm discrete bodies with contact defined between each discrete body and the corresponding ulnar and radial cartilage.[26,34] The humeral local coordinate system was taken as a reference to define the radial and ulnar coordinate system.[26] Internal rotation of the ulna, varus-valgus laxity, and ulnar and radial displacement were evaluated with a computational multibody elbow model that is conducive to kinematic assessments.

The specimens were positioned so that the long axis of the humerus was parallel to the floor with the lateral epicondyle facing up and medial epicondyle facing down (Fig. 1). During application of a gravity load at 90° of forearm pronation, the elbow was passively and continuously flexed from 30° to 120°. The hand, forearm, and upper arm MRI-derived skin geometries were used to compute the mass and inertia properties of each body segment. A

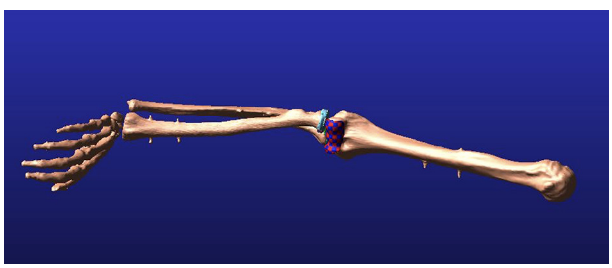

Figure 1 Cadaveric elbow model of specimen 1 aligned in pronated varus gravity position.

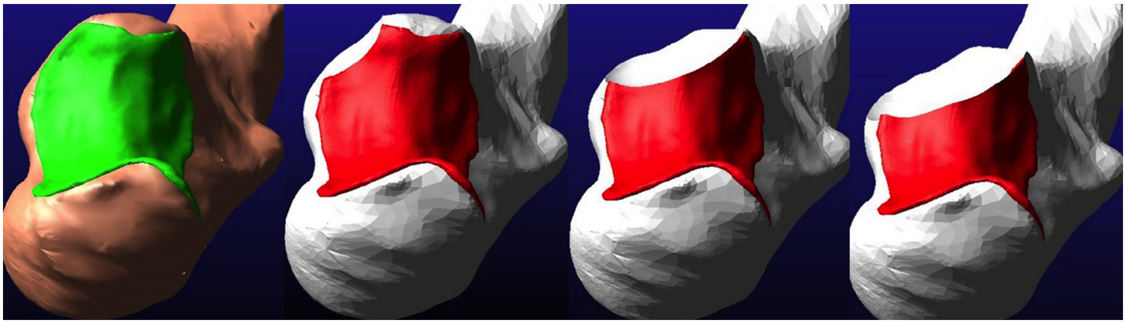

Figure 2 Posterior view of specimen 1 elbow. The intact coronoid and concave fracture patterns of trochlear impaction simulating subtype I, subtype II 2.5-mm, and subtype II 5-mm anteromedial facet fractures are shown (from *left* to *right*).

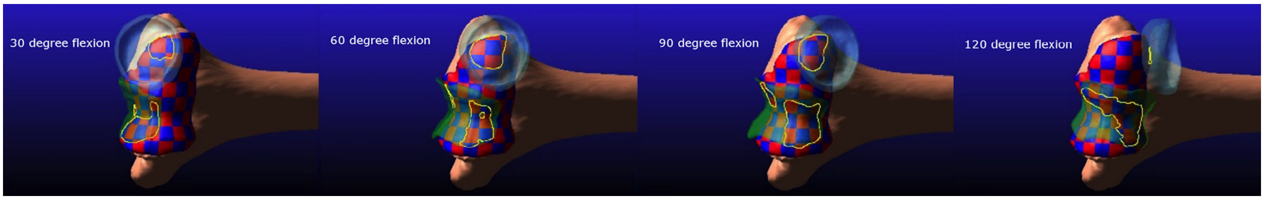

Figure 3 Contact areas on intact coronoid in specimen 1 during 30°, 60°, 90°, and 120° of flexion (from *left* to *right*). *Green* represents the ulnar articular cartilage, *faint blue* represents the radial articular cartilage, and *yellow lines* outline the contact areas. The *checkered red-blue areas* represent the humeral articular cartilage.

gravity force field was then applied in the medial direction along the elbow joint axis. To flex the joint, the least amount of force necessary to induce flexion was applied at the center of mass of the forearm segment.

Injury conditions

Templating of fractures onto the anteromedial facet of the multibody models was performed, using the curvature of the trochlea, simulating the concave shape of impaction described by O'Driscoll et al.[20] Four different conditions were simulated in this study: (1) no fracture, (2) O'Driscoll anteromedial subtype I coronoid fracture (2.5-mm fragment), (3) subtype II with 2.5-mm fragment, and (4) subtype II with 5-mm fragment (Fig. 2). In each of these conditions, 3 ligament repairs were studied, resulting in a total of 16 conditions: LUCL-only repair, pMCL-only repair, and both LUCL and pMCL repair. Computationally, ligaments were modeled as force elements described by a force-length relationship.[25,26] To simulate the different ligament-repaired conditions, the ligament force elements were either turned on (simulating repaired ligament) or turned off (simulating torn ligament). Elbow articular contact areas were computationally calculated throughout the range of motion of each elbow compared with the native intact elbow.[27,34] Discrete cartilage bodies had a cross-sectional area of 25 mm^2, and any humeral cartilage body experiencing a contact force more than 5 N was included in the contact area calculation (Figs. 3-6).

For each condition, internal-external rotations and varus-valgus angulations of the ulna relative to the humerus were calculated and compared with the intact model simulation. The range of varus

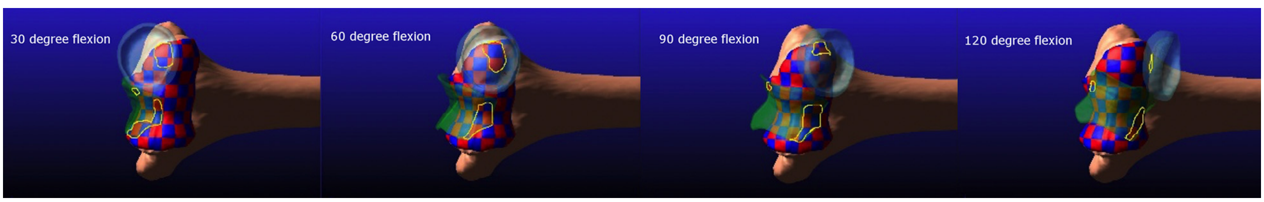

Figure 4 Contact areas in specimen 1 with subtype I fracture during 30°, 60°, 90°, and 120° of flexion (from *left* to *right*).

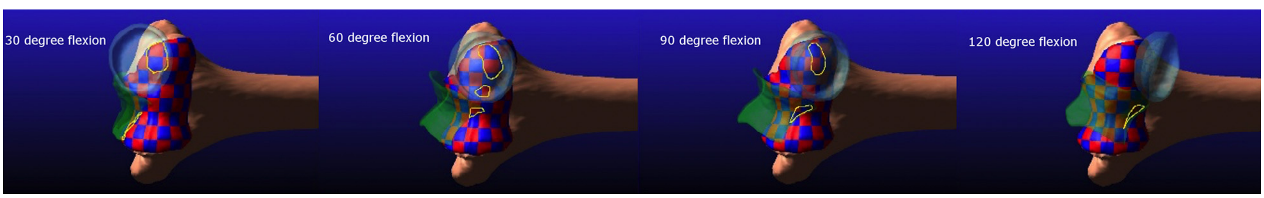

Figure 5 Contact areas in specimen 1 with subtype II 2.5-mm fracture during 30°, 60°, 90°, and 120° of flexion (from *left* to *right*).

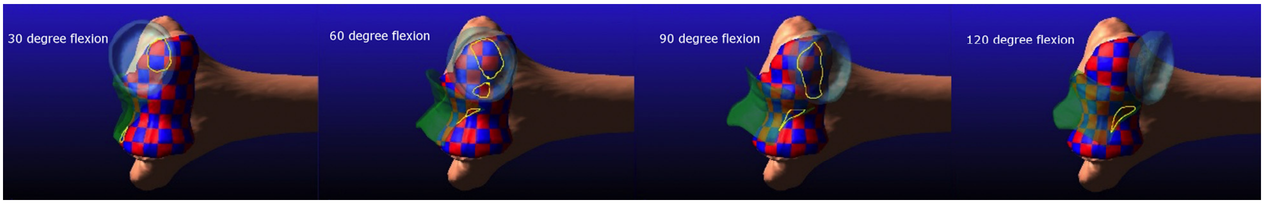

Figure 6 Contact areas in specimen 1 with subtype II 5-mm fracture during 30°, 60°, 90°, and 120° of flexion (from *left* to *right*).

to valgus angulation and rotational variability throughout the simulated range of motion were individually calculated in the specimens with intact ligaments and anteromedial facets. These calculated values were used as the acceptable laxity for tested conditions, meaning that the elbows were considered stable if the kinematic curve fell within this range. These ranges of laxity in an intact elbow plus or minus the individual kinematic curve for the elbow tested are represented by the shaded areas in Figure 7.

Data analysis

To determine the effects of individual components of the PMRI pattern, comparisons of kinematics and contact areas were made between the values recorded at the corresponding flexion angles for the tested condition and baseline comparison. These differences were measured and averaged, with reporting of their sum ± standard deviation.

Results

The variation in rotational motion throughout the tested range of motion was 3° for intact specimen 1 and 1° for specimen 2. For varus and valgus angulation, laxity was 2° for both intact specimen 1 and specimen 2 (represented by shaded areas in Fig. 7).

With both the LUCL and pMCL torn, when compared with an intact coronoid, subtype I fractures did not increase internal rotation in specimen 1 or 2. Subtype II 2.5-mm fractures increased internal rotation by 4° ± 3° and 3° ± 1° in specimens 1 and 2, respectively. Subtype II 5-mm fractures increased internal rotation by 4° ± 3° and 5° ± 1° in specimens 1 and 2, respectively.

From the tested conditions with both the LUCL and pMCL torn, the isolated LUCL repair increased internal rotation, regardless of testing the intact coronoid or fracture subtype. In contrast, isolated pMCL repair decreased internal rotation when compared with the corresponding injury tested with both ligaments torn (Fig. 7, *A*). For the isolated repair of the LUCL, internal rotation of the ulna increased by 5° ± 1°, 3° ± 2°, and 5° ± 3° in the simulated subtype I (2.5-mm), subtype II 2.5-mm, and subtype II 5-mm anteromedial coronoid fractures, respectively, on average throughout the flexion arc tested for specimen 1 and by 2° ± 1°, 2° ± 1°, and 2° ± 2°, respectively, in specimen 2. During the same testing, the isolated repair of the pMCL decreased internal rotation of the ulna by 5° ± 3°, 6° ± 1°, and 5° ± 1° on average throughout the flexion arc tested for subtype I (2.5-mm), subtype II 2.5-mm, and subtype II 5-mm fractures, respectively, in specimen 1 and by 1° ± 1°, 2° ± 1°, and 4° ± 1°, respectively, in specimen 2. With both ligaments repaired, the combined internal rotation of the humerus was increased by 1° ± 2°, 0° ± 1°, and 1° ± 2°, respectively, in specimen 1 and by 1° ± 1°, 0° ± 1°, and 0° ± 2°, respectively, in specimen 2.

This experiment showed that in PMRI with subtype I (2.5-mm) fractures, repair of the LUCL restored kinematics that closely paralleled those of the intact and uninjured elbows' coronal-plane and rotational alignment simultaneously through the arc from 30°-85° of flexion in both specimens. However, when we tested an isolated repair of the pMCL in PMRI with a subtype I (2.5-mm) fracture, both angulation and rotation were acceptable from only 30°-50° in specimen 2 and were never both satisfactory simultaneously in specimen 1. In PMRI with a subtype I (2.5-mm) fracture, when both ligaments were repaired, the angulation and rotation were within the defined threshold throughout the arc of motion tested for both specimens.

In PMRI with subtype II 2.5-mm fractures, isolated repair of the LUCL or pMCL alone did not restore rotation or angulation when tested in gravity varus. When repairs of both the LUCL and pMCL were simulated, an acceptable kinematic pattern was obtained from 50°-110° in specimen 1 and 30°-50° in specimen 2. For larger fractures (subtype II 5-mm fractures), no combination of ligamentous repairs could restore varus and valgus angulation.

Figure 8 shows the cartilage contact area variations during flexion for all conditions for the ulna, radius, and total area. For all tested conditions, ulnohumeral contact increased with flexion whereas radiocapitellar contact stayed relatively unchanged. The combined contact area usually increased with increasing flexion angles. A common pattern observed in both elbows tested was that in the absence of the LUCL, contact between the radius and humerus was reduced especially for flexion angles larger than 80°. This finding corresponds with the widening of the radiocapitellar joint with varus stress at the elbow. In subtype I fractures, repair of both ligaments restored the ulnohumeral contact area close to that of the intact elbow. However, because of the articular bone loss (coronoid fracture), the ulnar contact areas were reduced in all subtype II fractures despite repair of both the LUCL and pMCL. The increase in fracture severity consistently decreased the ulnohumeral contact area throughout the flexion arc compared with the intact elbow despite the repair of both

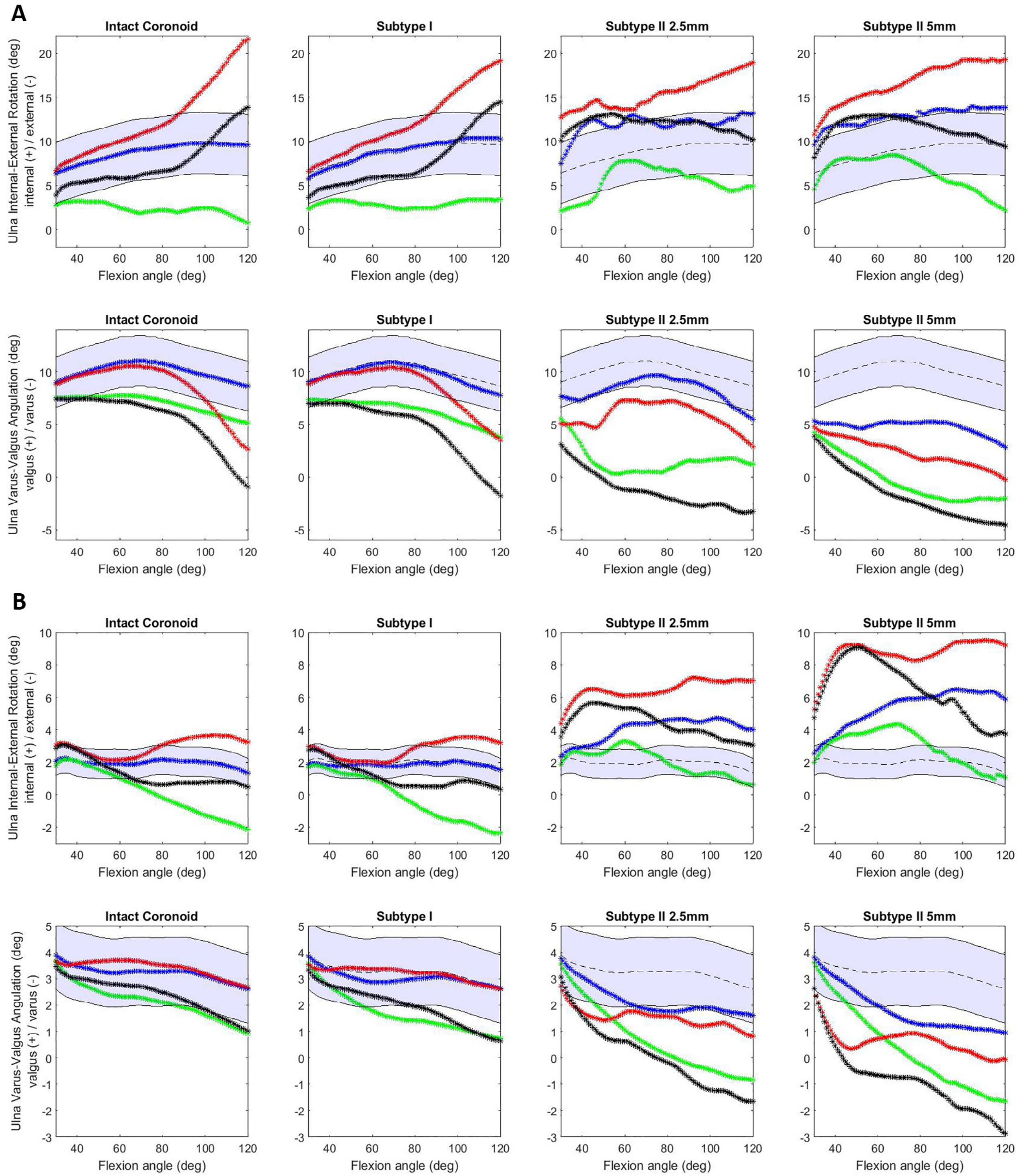

Figure 7 Ulnar rotational stability (*top row*) and varus-valgus angulation (*bottom row*) for intact coronoid and coronoid fracture patterns in specimen 1 (**A**) and specimen 2 (**B**). The *black lines* indicate both ligaments are torn; *red lines*, only the lateral ulnar collateral ligament is fixed; *green lines*, only the posterior bundle of the medial collateral ligament is fixed; and *blue lines*, both the lateral ulnar collateral ligament and posterior bundle of the medial collateral ligament are restored. The *dashed black lines* show the intact elbow. The variation of the respective rotational motion or angulation for the tested intact condition are represented in the *shaded areas*.

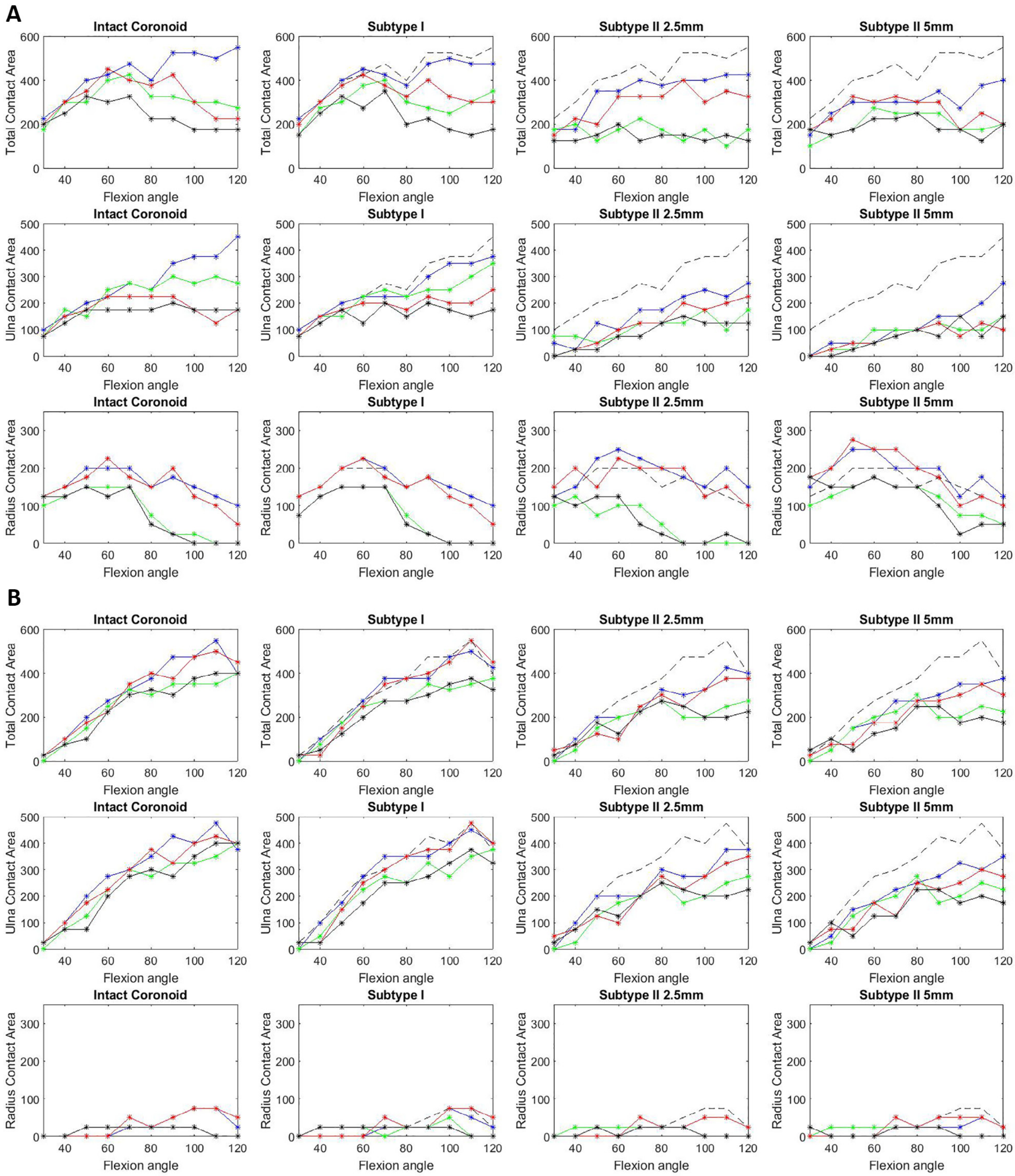

Figure 8 Contact area in square millimeters throughout arc of motion for intact coronoid and coronoid fracture patterns in specimen 1 (**A**) and specimen 2 (**B**). The *black lines* indicate both ligaments are torn; *red lines*, only the lateral ulnar collateral ligament is fixed; *green lines*, only the posterior bundle of the medial collateral ligament is fixed; and *blue lines*, both the lateral ulnar collateral ligament and posterior bundle of the medial collateral ligament are restored. The *top row* shows the total contact area; *middle row*, ulnar contact area; and *bottom row*, radial contact area. The *dashed black lines* show the intact elbow.

ligaments, as the elbows continued subluxating and hence undergoing edge loading of the trochlea on the fractured coronoid.

Discussion

From the limited amount of published literature, both coronoid fracture fixation and repair of the LUCL seem to be favored during the treatment of significant PMRI.[14,15,19,20,31,37] However, this treatment strategy is based on conclusions obtained from a small number of case series, cadaveric studies, and expert opinions with a low level of evidence at this time.[16,31,37,39] Our study analyzed various anteromedial coronoid fracture patterns with different combinations of pMCL and LUCL ligamentous repairs regarding elbow kinematics and articular contact areas in anatomic computational multibody elbow joint models. To our knowledge, no study to date has evaluated repair of either or both ligamentous injuries associated with anteromedial coronoid fractures. This study expands on previous work looking at isolated components of the injury and further expands on understanding the effects of ligamentous repair with respect to elbow varus and valgus angulation, internal-external rotation, and contact areas.

The importance of the coronoid fragment size has been highlighted in determining treatment strategies in cadaveric and clinical studies.[21,22,28] Several studies showed differing results for similar repair strategies.[1,5,12,22] Pollock et al[22] suggested fixation for subtype I (>5-mm), subtype II (>2.5-mm), and subtype III fractures. Unlike Pollock et al,[22] Rhyou et al[28] reported successful outcomes with only LUCL repair for PMRI with subtype I (>5-mm) and subtype II (2.5- and 5-mm) fractures. On the other hand, Bellato et al[5] found that the contact pressure in the ulnar-trochlear joint was still increased by 40% compared with the intact elbow in cadaveric models of PMRI with repaired LUCLs.

In most clinical studies in which successful outcomes were obtained with conservative treatment for anteromedial coronoid fractures, the status of the pMCL and LUCL was unclear.[6,10,38] Thereby, it is difficult to know the number among the reported cases that actually had PMRI. The discrepancy might be a result of treatment outcomes of the patients in whom PMRI was incorrectly diagnosed. Only in the study performed by Doornberg and Ring[8] was pMCL and LUCL injury documented operatively. They have reported unsuccessful outcomes in cases with conservative treatment or with surgical treatment with inadequate fixation. In light of these results, we believe that PMRI especially with larger fractures may not be managed with conservative treatment.

The current understanding of the function and importance of the pMCL is rudimentary, and this is a neglected but emerging area of interest among PMRI researchers and clinicians. This is because, clinically, the LUCL is often repaired yet few surgeons repair the pMCL. One reason is the familiarity with LUCL repair and its well-established repair techniques. Another reason is the thought that the medial collateral ligament (MCL) can be intact in patients with anteromedial coronoid fractures[8] or effects on elbow kinematics can be considered clinically insignificant.[2] Some authors have even reported that MCL injuries can heal spontaneously.[9] However, there is emerging literature about the functional importance of and, more recently, surgical repair techniques for the pMCL.[5,23,33,35] Golan et al[12] reported that pMCL injury might be the cause of the persistent instability of the elbow despite the fixation of the anteromedial coronoid and LUCL repair in PMRI. However, no author has reported on the clinical results of pMCL repair. Sard et al[33] stated that the pMCL is a primary stabilizer of the elbow against valgus stress. They also reported satisfactory biomechanical results with the pMCL reconstruction technique that they described. Morrey[18] suggested MCL repair for persisted instability despite the fixation of the fracture and LUCL repair. Moreover, Morrey[17] reported on a patient with posteromedial rotatory incongruity treated with only reconstruction of the pMCL.

In our study, kinematic angulation and rotational analysis of the repair techniques has delineated that some larger fracture patterns will necessitate combined bony and ligamentous repair; however, some smaller fractures may be treated with ligamentous repair alone if range of motion is protected. This study confirms the prior published literature showing that no ligamentous repair tested would be sufficient to restore acceptable kinematics in subtype II 5-mm fractures; thus, these fractures would require reduction and fixation in combination with ligament repair or reconstruction.

Our results are similar to those reported by Pollock et al[22] and can be attributed to the similar method of testing; both studies tested specimens in gravity varus with the forearm held in full pronation throughout the tested arc. The findings presented in both studies corroborate that ulnar internal rotation increases with ligamentous deficient elbows that have progressively larger and more advanced subtypes of anteromedial fractures. Furthermore, the repair or reconstruction of the LUCL increased internal rotation in both studies. In their study, Pollock et al[22] found that pMCL deficiency did not increase internal rotation and varus. However, our study determined that pMCL deficiency alone caused an increase in internal rotation, as well as varus angulation, and it was an important factor in the formation of PMRI-specific elbow kinematics. Pollock et al,[23] in another study, compared pMCL-deficient elbows with intact elbows and reported that pMCL injury actually increased varus angulation by 3.5° and internal rotation by 1°.

There are possible reasons for these differences in the findings. PMRI-specific concave fracture patterns were used in our study, whereas a convex pattern was simulated by Pollock et al.[23] We believe that the concave fracture configuration due to impaction from the humeral trochlea as described by O'Driscoll et al[20] is crucial for PMRI. Bellato et al[5] asserted that the concave fracture edge might be responsible for the rapidly progressive osteoarthritis in PMRI by scraping the humeral trochlea.

In our study, for subtype I (2.5-mm) fractures, only LUCL repair was sufficient to regain acceptable angulation, rotation, and contact areas for an arc avoiding deep flexion, mostly corroborating the findings in the literature. Pollock et al[22] reported that acceptable elbow kinematics were obtained for small subtype I (2.5-mm) fractures even if the LUCL was not repaired. Successful outcomes with conservative treatment have been reported for small subtype I fractures with minimal displacement in clinical studies.[6,10,21] Because of the increased internal rotation that can occur in the deficient pMCL setting by repair of the LUCL, we recommend obtaining and maintaining reduction of the elbow joint before finalizing the LUCL repair.

In subtype II 2.5-mm fractures, perfect repair of both medial and lateral ligaments allowed for acceptable angulation and rotation but not for contact areas through the midportion of the arc tested. In addition, similar to the findings of Pollock et al,[22] acceptable kinematics were not achievable with the isolated LUCL repair because internal rotation increased with the fracture and repair. The improvement in rotational alignment from the pMCL repair counterbalances the cumulative effect of the fracture and LUCL repair on kinematics, and thus, clinicians should have a stronger clinical consideration of pMCL repair especially with suboptimal fracture fixation due to comminution or smaller fragments. Clinically, Rhyou et al[28] performed isolated LUCL repair in 2 patients with small subtype II fractures and reported excellent outcomes at a mean follow-up of 42 months.

In subtype II 5-mm fractures with repaired ligaments, we not only could not restore favorable kinematics but also were not able to restore the articular contact areas close to the preinjury level, similar to the findings of Bellato et al.[5] Similarly, the isolated LUCL repair for PMRI with subtype II 5-mm fractures resulted in varus and rotational instability, similar to the findings in the study of Pollock et al.[22] They suggested that these fractures must be managed with fracture fixation. Bellato et al[5] showed that reconstruction of the coronoid with a radial head or olecranon tip allograft could restore contact pressure if the fragment was not large enough for fixation. In a study by Park et al,[21] 4 cases with large subtype II fractures were treated operatively. In 3 cases, the LUCL and MCL were repaired and the fractures were fixed. The remaining case was treated by fracture fixation and LUCL repair. In 3 patients, the MCL was addressed surgically because stability could not be obtained despite fixation of the fracture and repair of the LUCL. Park et al reported favorable outcomes in these 3 patients at 31 months' follow-up and a fair outcome in the patient treated without MCL repair.

In our study, the total contact area decreased in elbows affected by PMRI, similar to cadaveric studies.[3,5] We believe this happened because of the loss of articular coronoid cartilage, as well as the subluxation that occurred owing to gravity varus loading of the elbows throughout the arc of flexion. In this study, we did not notice a spontaneous reduction of the ulnohumeral joint with flexion, which contributed to edge loading and hence decreased articular contact. Plausible contributors to this observation are that specimens in this study were tested without the use of axial muscle loads and full pronation was held throughout the range of motion to simulate maximum stresses on the elbow during early postoperative recovery for a typical activity such as drinking water from a bottle.[4,5,13,24] Thus, concavity compression was not initiated to reduce the joint nor was gravity alone used to define the pronation tested through the arc. In addition, in our model, neither the flexor-pronator group attachment nor the wrist extensor group attachment was kept intact, and the stability of the entire model depends on articular contact, the LUCL, and the MCL. Rhyou et al[28] have reported that LUCL injury concomitant with extensor muscle-tendon injury, defined as a "complex dual lesion," was more frequent in patients with positive varus stress test findings. Our goal is to incorporate the extensor and/or flexor-pronator muscle groups into the multibody framework in future models. Finally, in our model, full restoration of the ligaments including their perfect anatomic origin, insertion, and viscoelastic properties can be replicated rather than the surgical technique–dependent LUCL reconstruction with suture material that has been used by Bellato et al[5] in their study.

Computation modeling allows for repeated testing in the gravity varus position without the effects of ligamentous fatigue, as well as the ability to measure through the continuous arc with or without simulated muscle loading, while allowing for more extensive combinations of injuries and repairs. The simulations show anatomically perfect repairs. In cadaveric studies, it is difficult to obtain standard and equal ligament tension on each specimen with a ligament repair. For example, Fraser et al[11] have calculated that the optimum LUCL tension should be 20 N. They have reported that slightly more tension than this value was enough to induce a significant increase in internal rotation. Computational modeling that mimics a perfect LUCL repair may be more advantageous than cadaveric studies in terms of standardization, and more important, by using cadaver-specific values rather than literature generalizations, it should help increase the accuracy of the outcomes. Computational ligaments, with material properties of the native ligaments, can be restored fully to the preinjury level without the effects of individual surgical variations of ligamentous and fracture repairs; comminution of the fracture; and variable anatomic insertion of the ligaments, exposure, materials used for reconstruction, or surgical technique. In addition, microinstability—which is an important problem in the recording of the contact pressures in cadaveric studies[5]—was theoretically eliminated in our study. In clinical studies, the size of the coronoid fragment may not be created or measured accurately because of fragmentation and impaction. We believe that another strong aspect of our study is that standardized fractures in size and configuration created with the multibody model could be used.

This study has limitations associated with the use of computational modeling for data acquisition. We used values calculated from the specimens' intact ligamentous structures to model how an anatomically perfect repair would be represented. The isolated LUCL and MCL injuries and their repairs were tested previously in cadavers and their respective models[11,12,25,35]; however, the coronoid fracture model has not been tested in cadavers and was created only computationally for the purpose of this study. Moreover, individual repair techniques were not tested and are out of scope of this article. Another limitation is that the discrete rigid bodies used for the articular cartilage had an average cross-sectional area of 25 mm^2, thus limiting the resolution of contact area calculations. Our study had only 2 specimens; statistical interspecimen comparison is currently unable to be performed. Further expansion of the specimens tested would provide us with confidence that our findings are reproducible. In addition, incorporating the joint capsule, extensor and/or flexor-pronator muscle groups, and finite element cartilage modeling in the multibody framework can ensure improved predictions of contact pressure and kinematics.

This is the first study in which combinations of pMCL and LUCL ligamentous repairs were analyzed by evaluating kinematics and contact areas. However, it must be noted that the findings obtained in our study should be supported by further multibody models, as well as clinical trials.

Conclusion

This study's findings suggest that LUCL repair alone is sufficient to restore kinematics and the elbow contact area for small subtype I fractures for an arc avoiding deep flexion, whereas nearly normal kinematics and a nearly normal ulnar contact area throughout the arc of motion can be achieved if the pMCL is also repaired. For small subtype II fractures, ligamentous repair alone may not reliably restore kinematics or the elbow articular contact area. Larger fractures of the anteromedial coronoid should ideally have the fragments fixed or reconstructed if comminution prevents fixation. For all subtypes of anteromedial coronoid fractures, repair of the LUCL might result in more internal rotation if the fractures cannot be fixed anatomically and the pMCL is not addressed.

Disclaimer

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