Three-dimensional in vivo kinematics during elbow flexion in patients with lateral humeral condyle nonunion by an image-matching technique

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Background: An established nonunion of the lateral humeral condyle often reveals elbow instability and accompanying pain. The purpose of this study was to obtain 3-dimensional and quantitative information about the pathologic kinematics of the ulnohumeral joint with nonunion of the lateral humeral condyle by an in vivo and 3-dimensional motion analysis.

Methods: Magnetic resonance or computed tomography images of the elbows of 14 patients were acquired in 3 positions between full extension and full flexion. We evaluated ulnohumeral motion and calculated the change in the length of the medial collateral ligament during elbow flexion.

Results: Ulnohumeral motion was associated with an excessive lateral shift of ulnar movement. In addition, the distal part of the ulna was rotated in the varus direction, leading to a decrease in the carrying angle. The ulna tended to exhibit internal rotation from full extension to 90° of flexion of the elbow. With further flexion, the ulna rotated externally and returned to its neutral position. Furthermore, the length of the medial collateral ligament increased with an increase in the elbow flexion angle.

Conclusion: Patients with lateral humeral condyle nonunion showed excessive lateral shift of the ulna and ulnar axial rotation. Also, the lateral shift caused an osseous protrusion of the medial trochlea, leading to elongation of the medial collateral ligament.

Level of evidence: Basic Science Study, Kinesiology.

Keywords: Elbow; in vivo; three-dimensional kinematics; medial collateral ligament

Patients with nonunion of the lateral humeral condyle often have tardy ulnar nerve palsy in addition to painful symptoms caused by instability of the nonunion. Numerous reports have shown that ulnar nerve palsy is a frequent late consequence of cubitus valgus arising from malunion or nonunion of lateral condylar physis fractures. The outcomes of surgical
treatment for ulnar neuropathy caused by valgus deformity are reportedly worse than those of surgical treatment for idiopathic ulnar neuropathy.\textsuperscript{2} Although cubitus valgus during elbow extension (increased carrying angle) is thought to be a risk factor for nontraumatic ulnar neuropathy,\textsuperscript{4} the prophylactic value of correcting a valgus deformity to avoid neuropathy remains uncertain.\textsuperscript{17}

We speculated that the uncertainty of correcting a valgus deformity may be attributed to pathologic kinematics caused by a fracture nonunion, especially the pathologic kinematics of the ulnohumeral joint. However, the exact mechanism of instability is still unknown.

Recently, it has become possible to measure 3-dimensional (3D) kinematics in vivo with 3D computed tomography (CT) or magnetic resonance imaging (MRI). These techniques use image matching, also known as a registration technique, by CT or MRI to determine the corresponding relationships between images that represent different coordinates.\textsuperscript{15} By use of this methodology, 3D kinematics of the elbow joint can be analyzed accurately.\textsuperscript{12}

In addition, the in vivo 3D ligament length can be calculated noninvasively.\textsuperscript{20} To our knowledge, no studies have specifically evaluated elbow instability due to an established nonunion of the lateral humeral condyle or measured the change in length of the medial collateral ligament (MCL) during elbow flexion. By measuring the change in ligamentous length, we may predict what part of the ulnohumeral joint moves in an erratic manner.

This study aimed to evaluate in vivo 3D kinematics of established nonunions of the lateral humeral condyle during elbow flexion. In particular, we focused on lateral/medial ulnar shift, axial rotation, and valgus/varus rotation of the ulna at the ulnohumeral joint. In addition, we investigated changes in the length of the MCL during elbow flexion, specifically of the abnormal anatomic orientation and movement of the ulnohumeral joint. This study may provide additional knowledge to surgeons about the optimal treatment of the established nonunion of the lateral humeral condyle to avoid the uncertainty of correcting a valgus deformity.

Materials and methods

Patients

We evaluated 14 elbows of 14 patients (11 men, 3 women; average age, 47.4 years ranging from 26 to 63 years; Table 1). The time from injury to this study ranged from 20 to 58 years (average, 42.5 years). Clinically, all these patients were diagnosed with post-traumatic neuropathy. The time between injury and occurrence of ulnar palsy ranged from 9 to 54 years (average, 28.8 years). Regarding prestudy treatment of the fractures, 8 patients were immobilized with casts and 3 patients with splints for a mean of 5.3 weeks (range, 4-6 weeks). The remaining 3 patients did not have accurate diagnosis and did not undergo treatment. In all patients, numbness and tingling of the fifth finger were observed. All but one had decrease in 2-point discrimination. In 5 patients, weakness and atrophy of the abductor digiti minimi muscle were observed, and 4 of these patients had weakness and atrophy of both the abductor digiti minimi and first dorsal interosseous muscles. Nine patients subsequently underwent surgery after this study: 6 underwent anterior transposition of the ulnar nerve for alleviation of symptoms; 2 underwent anterior transposition and osteosynthesis for nonunited fracture; and 1 underwent anterior transposition, osteosynthesis, and corrective osteotomy for valgus deformity. The remaining 5 patients underwent conservative treatment. None of the other patients were treated for their symptoms.

Patient classification and evaluation by radiography

By use of anteroposterior and lateral radiographs, all patients were assigned Milch type II injuries.\textsuperscript{17} The average carrying angle was $22^\circ \pm 8^\circ$ (range, $10^\circ$-$40^\circ$).

Methods

The analysis protocol of this study, including the image-matching technique, was described previously.\textsuperscript{13} The 3D motion analysis included image acquisition, image matching (voxel-based registration), and 3D visualization. A mathematical description of the motions of individual bones and their relative motions was derived by computing the rigid transformation required to match the images to each other by position. We then calculated the shortest 3D path between the origin and insertion of the MCL on the basis of anatomic studies.\textsuperscript{5,20}

Image acquisition

Imaging was performed in 3 elbow positions: full extension, $90^\circ$ of flexion, and full flexion. During this study of elbow motion, the forearm was fixed in the neutral position. MRI data of 4 elbows were obtained with a 1.5-T MRI system (Magnetom Vision Plus 1.5-T MRI; Siemens AG, Erlangen, Germany) in conjunction with a receive-only body-array surface coil. We used a 3D sequence (3D flash) with a TR/TE/flip angle of 2.3 milliseconds/33 milliseconds/45\textdegree, a $256 \times 200$ in-plane acquisition matrix, and a 350-mm field of view and 2.0-mm thickness on a contiguous slice with a pixel size of $0.6 \times 0.8$ mm. The remaining 10 elbows were scanned with CT (LightSpeed Ultra 16; GE Medical Systems, Waukesha, WI, USA; scan time, 60 seconds; scan pitch, 2 mm; 80-100 mAs; 120 kV; slice thickness, 0.5 mm). To minimize radiation exposure, CT parameters were set at approximately 1/3 of the clinically established tube current. Although 3D bone models constructed from 1/30 low–radiation dose CT data reportedly provided the same level of accuracy as those constructed from normal–radiation dose data,\textsuperscript{20} the patients in this study had decreases in bone densities at the lateral humeral condyles and thereby we decided to choose this protocol in this study. Image data were saved in Digital Imaging and Communications in Medicine (DICOM) format, which is commonly used for transferring and storing medical images.

Image matching (voxel-based registration) and making of 3D surface bone models

In the initial phase, regions of individual bones were semi-automatically separated and extracted from magnetic resonance and CT images by a 3D region-growing method. Then, the
segmented bones were superimposed on images of the same bones in each subsequent position by use of a voxel-based registration technique. Voxel-based registration, which is based on the similarity measurements of image intensities, is a method for determining the relative positions between 3D images that represent different coordinates (different joint positions). The in vitro cadaveric validation for this voxel-based registration technique using fiducial markers and CT imaging revealed an average rotational error of $0.6^\circ \pm 0.5^\circ$ and an average translation error of $0.7 \pm 0.6$ mm.\(^1\) This method using MRI had an average rotation error of $1.3^\circ \pm 1.0^\circ$ and an average translation error of $0.2 \pm 0.3$ mm.\(^1\) We analyzed only images of the left elbows; images of the right elbows were converted to mirror-image models. The software developed in our laboratory is based on the Visualization Toolkit (Kitware, Clifton Park, NY, USA) and generates 3D surface bone models from magnetic resonance and CT images by the marching cubes technique.\(^1\)

**Definition of the local coordinate system for the ulnohumeral joint**

The coordinate system and rotation order used in this study were constructed according to the International Society of Biomechanics definitions described by Wu et al.\(^{17}\): y-axis, axial rotation of the forearm, external rotation (negative), and internal rotation (positive); z-axis, flexion (negative) and hyperextension (positive); x-axis, varus rotation (negative) and valgus rotation (positive). The origin of the local coordinate system for the ulnohumeral joint was located on the articulating part of the medial condyle of the humerus.

**3D kinematics of the ulnohumeral joint**

A mathematical description of the motions of individual bones and their relative motions was derived by computing the rigid transformation required to match the images. Joint kinematics could be analyzed 3-dimensionally in terms of associated rotations and translations referred to the elbow joint–local coordinate system. We transformed images of the right elbows using mirror-transformation matrices. We then determined the transformation matrices of the ulna relative to the humerus. Using Euler angles, ulnar relative motion was decomposed into 3 rotation angles and 3 translations. In this study, we evaluated the amount of lateral/medial ulnar shift, which was one of the 3 translations. Also, during humeral flexion, we focused on the varus/valgus rotation (carrying angle) and the axial rotation of the ulna (external/internal rotation).

**Calculation of changes in the MCL length**

The 3D lengths between the insertion and origin of ligaments were determined as the shortest paths in 3D space along the surface of the bone models prepared with the CT data.\(^{20}\) In this algorithm, information on ligament attachments was obtained from an anatomic study.\(^9\) The anterior bundle of the MCL comprises anterior and posterior bands that are tightened in a reciprocal manner as the elbow is flexed and extended.\(^9\) One band included in the anterior bundle, which is always taut during elbow flexion/extension, serves to guide joint movements (guiding band).\(^9\) We evaluated 3 bands of the anterior bundle of the MCL, namely, the anterior, posterior, and guiding bands, as well as the posterior bundle of the MCL. We measured the lengths at 3 or 4 sites in each component on the basis of available anatomic information and averaged the values obtained, as shown in Figure 1. Also, the interobserver and intraobserver reliability of this measurement was assessed by Pearson correlation coefficients. The Pearson correlation coefficient was calculated and compared between the 2 different observers (interobserver reliability) and between repeated measurements by each of the 2 observers (intraobserver reliability) for each of the measurements.

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**Table 1**  Patient Characteristics

<table>
<thead>
<tr>
<th>Side</th>
<th>Presenting symptoms</th>
<th>McGowan’s grade(^2)</th>
<th>Toh’s radiographic criteria(^4)</th>
<th>Carrying angle (degrees)</th>
<th>Range of motion (degrees)</th>
<th>Image modality</th>
<th>Treatment</th>
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<td>Ulnar nerve dysfunction</td>
<td>II</td>
<td>Group 2</td>
<td>14</td>
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<td>Anterior transposition</td>
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CT, computed tomography; MRI, magnetic resonance imaging.
Statistical analysis

Data were analyzed by the JMP version 9 software package for Windows (SAS Institute, Inc, Cary, NC, USA). Analysis of the distribution of constant variance for normality was assessed by the Shapiro-Wilk test. The data of the different groups were checked for homoscedasticity by Levene tests. Finally, the data for all sequential elbow flexion positions were statistically analyzed by 1-way repeated-measures analysis of variance and a post hoc Tukey-Kramer test. P < .05 was considered statistically significant.

Results

3D kinematics of the ulnohumeral joint

During elbow flexion, 3D ulnohumeral motion showed a lateral shift in ulnar movement at the elbow joint, whereas the distal part of the ulna rotated in the varus direction, thus decreasing the carrying angle. These movements increased according to the elbow flexion angle (Fig. 2). The average lateral shifts of the ulna at 90° of flexion and full flexion were 11 ± 10 mm (P = .00069) and 17 ± 12 mm (P < .0001), respectively; these values were significantly higher than those for full elbow extension (Fig. 3).

The increase in varus rotation was almost linearly proportional to the elbow joint flexion angle (Fig. 4). The ulna exhibited 19° ± 18° of varus rotation from full extension to 90° of flexion (P = .0015). Varus rotation then increased significantly by 17° ± 11° from 90° of flexion to full flexion (P = .0062). It increased to 36° ± 15° at full flexion.

Regarding ulnar axial rotation, the ulna tended to show internal rotation from full extension to 90° of flexion. With further elbow flexion, the ulna rotated externally and returned to its neutral position. An average angle of 17° ± 14° forward to the internal rotation was observed from full extension to 90° of flexion (P = .0011). The average axial rotation of the ulna from 90° of flexion to full flexion was 17° ± 13° in the opposite direction (external rotation; P = .0008). External rotation in the forearm was 0° ± 13° at full elbow flexion (Fig. 5).

Changes in MCL length

Both interobserver reliability and intraobserver reliability were found to be more than 0.98 for all measurements. The 3D animations for ligament lengths showed that the ligament paths were kinked by an osseous protrusion of the
medial trochlea (Fig. 6). The anterior bundle as well as the posterior bundle elongated with increasing flexion. In addition, isometric bands and a bundle were not found within the MCL (Fig. 7). The guiding band exhibited the greatest increase in length, with an average increase of 14 ± 5 mm from full extension to full flexion (P < .0001). At full extension, this band was 17 ± 3 mm long. Its length increased by an average of 6 ± 5 mm from full extension to 90° of flexion (P = .0009). It then increased by an average of 7 ± 4 mm from 90° of flexion to full flexion (P = .0015).

A similar trend was observed for posterior bundle elongation; this bundle exhibited the second greatest increase in length. On average, the change in posterior bundle length was 12 ± 7 mm throughout the arc of flexion (P < .0001). At full extension, 90° of flexion, and full

Figure 2  In the top row images, the lateral shift of the ulna at the elbow joint is increased according to the elbow flexion angle (yellow arrow), whereas the distal part of the ulna has moved medially (decreased carrying angle; light blue arrow). The edge of the medial trochlea is protruding away from the edge of the olecranon because of the lateral shift of the proximal ulna. In the bottom row images, during 90° of flexion (blue counterclockwise curved arrow), the olecranon of the ulna is internally rotated, moving the lateral condyle upward (yellow upward arrow). With further elbow flexion, the olecranon is rotated in the opposite direction (external rotation; blue clockwise curved arrow), moving the lateral condyle downward (yellow downward arrow).

Figure 3  Line graph showing the change (and standard deviation) in the extent of lateral ulnar shift during elbow flexion. The vertical axis shows the amount of lateral shift during humeroulnar flexion, and the horizontal axis shows the elbow position angle. The lateral shift significantly increased according to the elbow flexion angle. *Significant differences between each measurement group (P < .005).

Figure 4  Line graph showing varus/valgus rotation (carrying angle). The vertical axis shows the amount of varus rotation of the ulna during humeroulnar flexion (+/valgus rotation, −/varus rotation), and the horizontal axis shows the elbow position angle. A linear increase in varus rotation angle was observed throughout the arc of elbow flexion.
nerve, we questioned whether cubitus valgus deformity is alone does not always alter the vulnerability of the ulnar nerve. During elbow flexion, the length of the posterior bundle was 18 ± 7 mm, 24 ± 6 mm, and 30 ± 4 mm, respectively.

At full extension, the length of the posterior band of the anterior bundle was 27 ± 8 mm. This band also increased linearly with further elbow flexion; the total change in length was 12 ± 7 mm (P < .0001). In comparison, the anterior band of the anterior bundle exhibited the least change in length of all the bands and the posterior bundle; its length change was 5 ± 6 mm throughout the arc of flexion (P = .014). This anterior band may have functioned as an isometric band.

Discussion

As treatment for correction of a cubitus valgus deformity alone does not always alter the vulnerability of the ulnar nerve, we questioned whether cubitus valgus deformity is the only cause of neuropathy. Patients present with elbow instability symptoms when using their elbows. Also, it is possible that the ulnar nerve is predisposed to neuropathy during elbow flexion. We therefore speculate that elbow instability during elbow motion may be due to various causes, such as a lateral shift of the ulna, which may lead to kinks in the ulnar nerve. However, little attention has been given to elbow instability. One reason for this may be absence of quantitative measurements of the 3D kinematics. We used recently developed techniques in the current study that enable us to accurately evaluate the 3D movements of the joints and the change in length of curved ligaments. By measuring the change in ligamentous length, we may evaluate what part of the joint moves in an erratic manner.

In our results, the distal part of the ulna rotated in the varus (medial) direction, decreasing valgus angulation (carrying angle), and the proximal part of the ulna exhibited a lateral shift. The edge of the medial trochlea protruded away from the edge of the olecranon, showing an increase with further elbow flexion (Fig. 2). In our previous study, we reported on the normative elbow kinematics by use of our methods. Such osseous protrusion of the medial condyle was not observed in normative data. It is possible that the ulnar nerve is kinked and compressed by this osseous protrusion. We think that ulnar neuropathy might be attributed largely to the protrusion of the medial trochlea. In addition, axial rotatory instability of the ulna was observed. Although axial rotation of the ulna has been observed during passive flexion of the normal elbow, the ulna internally rotates up to 5° when the forearm is supinated; maximum axial rotation of the ulna occurs in this position compared with the other forearm positions. We found that in comparison with a database of normal elbows obtained in the previous study, elbows with nonunion of the lateral humeral condyle were unstable in the lateral direction and around the axis of the forearm during flexion. These elbow instabilities may have caused the ulnar nerve to stretch over the crest of the medial trochlea and to become twisted.

Regarding the ligamentous length of the MCL, Morrey and An reported that the length of the anterior bundle was 27 ± 4.3 mm and that of the posterior bundle was 24 ± 4 mm during elbow extension. The length of the anterior bundle increased from extension to approximately 60° of flexion; thereafter, it remained nearly constant. The average change in the length of the anterior bundle was 5 mm throughout the arc of elbow flexion. Also, regarding the change in length of the posterior bundle, a linear increase was observed after 60° of flexion; this increased by 9 mm from 60° of flexion to 120° of flexion.27 We also reported on the change in the ligamentous length using the in vivo 3D motion kinematics, which was similar to Morrey and An’s results. In our results of this study, the average increase in the guiding and posterior bands was 14 ± 5 mm and 11 ± 5 mm, respectively. The average increase in the anterior bundle was 5 ± 6 mm, which was almost the same as that reported by Morrey and An and our previous study. The length of the posterior bundle increased by an average of 12 ± 7 mm; this increase was greater than that reported in a previous study (9 mm). Compared with the study by Morrey and An and our previous study, all parts of the MCL in our study were excessively elongated according to the flexion angle, except for the anterior band. The anterior bundle of the MCL is the primary stabilizer to resist valgus stress at the elbow. In addition, it reportedly limits the internal rotation of the ulna during elbow flexion. In a study of sequential sectioning of the MCL in test and control subjects, Morrey et al noted that an anterior bundle deficit results in a loss of this constraint, which allows the elbow to exhibit increased internal ulnohumeral rotation. Regarding the posterior bundle of the MCL, it has been shown to have a secondary role as a varus and rotational stabilizer. Also, several studies demonstrated...
that the posterior bundle of the MCL provided a valgus stability at elbow flexion.5,9,14,21 On the basis of previous studies and our results, we could predict that the MCL in patients with a nonunion will not work normally and may be functionally deficient during elbow motion. Especially the posterior part of the MCL (except for the anterior band) elongated significantly with progressive flexion. We can assume the elongation of the posterior part of the MCL as the lateral shift of the olecranon as shown in Figure 6.

Elbow instability may be attributed primarily to the mobility of the nonunion fragment. A previous biomechanical study defined the radial head as a secondary constraint to valgus instability after the anterior bundle.16 Although we did not evaluate the extent of mobility of the nonunion in this study, we speculate that excessive movement of a nonunion is similar to elbow instability caused by excision of the radial head and that this movement will eventually result in elbow instability. Whether nonunion of the lateral humeral condyle should be treated by osteosynthesis or left alone remains controversial.8,14 However, in our opinion, nonunion of the lateral humeral condyle accompanied by refractory nerve injury and excessive instability may require osteosynthesis to minimize the movement of the nonunion and to prevent excessive movement of the ulna. We believe that these findings provide additional information that can aid surgeons’ decisions about surgical treatment for instability of a nonunion or functional insufficiency of the MCL.

This study had several limitations. Our measurements were estimated under sequential static conditions, which may not accurately reflect the actual events occurring during dynamic activities. We did not perform contralateral elbow imaging to obtain normative data for a control group. However, we reported on the normative data in our previous study.12,24 Also, our results in this study differed from previous normative data. Regarding calculation of changes in the MCL length, the origins and insertions of ligaments

![Figure 6](image1)

**Figure 6** Change in length and path represented by curved lines in 3D bone models. During elbow flexion, all the bands of the anterior bundle as well as the entire posterior bundle of the medial collateral ligament were stretched and kinked by the edge of the medial trochlea, which protruded away from the edge of the olecranon. The greatest ligament elongations were observed during full elbow flexion.

![Figure 7](image2)

**Figure 7** Change in length of the medial collateral ligament (MCL) during elbow flexion. **Blue line**, the anterior band of the anterior bundle of the MCL. **Red line**, the posterior band of the anterior bundle of the MCL. **Yellow-green line**, the guiding band of the anterior bundle of the MCL. **Purple line**, the posterior bundle of the MCL (POL). All bands of the anterior bundle as well as the posterior bundle elongated with increasing flexion. The guiding band (yellow-green line) exhibited the greatest increase in length ($P < .0001$). In contrast, the anterior band of the anterior bundle (light blue line) exhibited the least change in length of all the bands of the anterior bundle and the entire posterior bundle ($P = .014$).
were determined only on the basis of anatomic information obtained from previous literature. Although these measurements could not reflect the actual ligament lengths in each subject, we assume that the changes in lengths documented in our study exerted an important influence on the functions of soft tissue stabilizers and could be essential in considering elbow kinematics. We evaluated only patients with tardy ulnar nerve palsy. It would have been better to analyze the relationship between ulnar nerve palsy and elbow instability in patients with and without nerve palsy. Therefore, a larger number of patients will be required in future research, which should include patients with and without tardy ulnar nerve palsy.

Conclusions

We found that in comparison with intact elbows, elbows with nonunion of the lateral humeral condyle were unstable in the lateral direction and around the axis of the forearm during flexion. Therefore, treatment for nonunion of the lateral humeral condyle accompanied by refractory nerve injury and excessive elbow instability may require osteosynthesis to minimize movement of the nonunion and to prevent the ulna from undergoing excessive movements.

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