The role of the interosseous ligament in forearm rotation: A bio-mechanical study

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Abstract
Background: Management of longitudinal forearm instability remains challenging. Chronic forearm stability may be overcome by reconstruction of the interosseous ligament (IOL). Despite the bands of the IOL being inseparable, studies of the IOL have focused on the central band (CB), but have neglected the proximal (PB) and distal (DB) bands. The purpose of this study was to characterize the bio-mechanical properties of the IOL. Materials and Methods: Twelve frozen specimens from individuals of both sexes were bio-mechanically analyzed using a custom-designed jig operated at constant angular speed to simulate forearm rotation. Strain was measured during dynamic forearm simulation using a motion tracking system. Results: The average strain of the CB, PB, and DB during forearm simulation were 0.08 ± 0.04, 0.83 ± 0.47, and 0.65 ± 0.23 mm (p < 0.001). The IOL was generally shortest during maximal pronation and increased as the forearm was rotated to a neutral position. The strain of the CB remain constant during forearm rotation and was the lowest at full pronation to 20° pronation position. Throughout forearm rotation, the strain of the CB remained constant, whereas the strain of the PB and DB fluctuated. Conclusions: The PB, CB, and DB of the forearm IOL have different bio-mechanical properties. CB maintained a constant rotational strain throughout forearm rotation. Strain on the CB was significantly lower than strains on the PB and DB. By contrast, strains on the PB and DB varied, suggesting that their roles differ from those of the CB. When CB reconstruction is needed, graft should be tensioned at 20° forearm pronation to gain optimum tension.

Keywords
bio-mechanical, forearm, interosseous membrane, ligament, strain

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Introduction
The interosseous membrane (IOM) of the forearm is regarded as a transitional segment from the elbow to the wrist. Studies focusing on the role of the IOM in forearm stability have indicated that the forearm is not a simple intercalated segment. Back lighting showed that a thicker central band (CB) of the IOM was located at the mid-span of the portion between the radius and ulna. The thickened appearance of the CB on gross inspection has indicated that the IOM should be classified as a ligament.

The primary stabilizer of the forearm is the radial head through the radio-capitellar joint, whereas the secondary...
stabilizers are the interosseous ligament (IOL) and the triangular fibrocartilage complex. Greater understanding of the IOL can help in determining the pathologic mechanisms associated with injury to and reconstruction of the IOL, particularly in regard to chronic Essex-Lopresti injury. From a mechanical perspective, IOL reconstruction may improve longitudinal instability, with many studies evaluating the association between IOL reconstruction and radial head replacement.10,11

Reconstruction of the IOL has been hampered by a great lack of understanding of strains on the IOL throughout forearm rotational motion. Despite many studies, the bio-mechanical characteristics of the IOL remain unclear.1,2,4,6,12–15 The present study therefore analyzed the bio-mechanical characteristics of the IOL in a dynamic setting.

**Materials and methods**

All specimens used in the current study were obtain from cadavers through donation process which were consented by next of kin. IRB was obtained prior to the study (2019-0969). Twelve fresh-frozen human forearm specimens of both sexes (six females and six males) were included in our study. The average age of the individuals was 63.5 (range, 45–70) years. The included individuals were with the mean body weight of 67.6 (range, 55–71) kg and mean body height of 161.6 (range, 155–167) cm. The full body cadavers had been sealed in polyethylene bags without embalming procedure and stored at −25°C freezer. The individuals were being stored for 10–14 days prior to thawing process. The medical records of all cadavers had been screened for previous history of upper limb pathology, including trauma, contractures, and collagen disorders, by two orthopedic surgeons (E.K. and Y.C.S).

**Gross tissue preparation**

Each forearm was cut to the mid-humerus level, thawed overnight at room temperature, and examined to document the range of prono-supination. Each specimen underwent single cycle of thawing process to avoid deterioration of bio-mechanical property. Each forearm was dissected under 2.5× loupe magnification to remove the overlying soft tissues and musculature, retaining only the IOL. The proximal and distal radioulnar joint were preserved. Metliculous care was taken to ensure that the IOL was well preserved. The IOL was kept moist throughout specimen preparation and testing with normal saline spray at room temperature. The CB was identified as the thickest band running from the proximal radius to the distal ulna and was confirmed by back lighting, as described.6 The proximal band (PB) and distal band (DB) were thinner and ran in the opposite direction to the CB.

**Experimental set-up**

A pilot test of one specimen was performed to establish the bio-mechanical testing protocol. During the dissection, one specimen was excluded because its condition had deteriorated. Therefore, the study included 10 specimens. The specimens were placed in a custom-made jig to securely hold the forearm while permitting controlled application of rotation movement. Rotation movements were set from 50° pronation to 50° supination, and resulted in a 100° motion arc, representing the range sufficient for most activities of daily living. Although the degree-of-motion arc may vary between men and women, and between individuals,17 the decision to set the motion arc at 100° was based on the reproducibility of the experimental set-up and its practicality for non-weighted data analysis.

Figure 1 shows the experimental set-up, and the speed of rotation movement was controlled by a customized servo-motor device. The ulna shaft was drilled and clamped to the fixed table to prevent movement. The distal radius was drilled and secured to the metal bar, which was linked to the servo-motor, allowing the radius to be rotated along the ulna at a constant angular speed of 4.75 rpm. Each specimen was subjected to three cycles of forearm rotation, each consisting of pronation-neutral-supination-neutral-pronation. The axis of rotation was determined as described.18

The experimental set-up was designed to avoid any metal reflection, reducing noise from the data. The measurement of strain were adapted from the previous literature which measure the strain of medial collateral ligament of the knee. An optical tracking system (OptiTrack, Natural Point, Inc., Corvallis, OR, USA), consisting of four large-volume-motion-capture cameras, was used to track the three-dimensional coordinate of each band (Prime 41; Natural Point, Inc.). The four cameras were organized in a semicircle to ensure their ability to capture the reflective markers. Reflective markers (4 mm Facial Markers, MCP1130, Opti-Track; Natural Point, Inc.) were attached to the origins and insertions of the ligamentous part of each IOL band, and to both the ulnar and radial styloids (Figure 2).

Pairs of reflective markers were placed at the PB, CB, and DB of the IOL at both the radial and ulnar sides. The trajectories of these markers were recorded with associated tracking software (Motive: Tracker; Natural Point, Inc.) at a sampling rate of 60 Hz, equal to 600 measurements of length for each specimen. During each forearm rotation, the optical motion markers recorded the motions, which were later transformed to determine the motion of the radius relative to the motion of the “fixed” ulna. For practical analysis, the in situ strain at each band was not measured and was assumed to be uniform.

**Statistical analysis**

All statistical analyses were supervised by a bio-statistician. The normality of data distribution was assessed
using the Kolmogorov–Smirnov test. All descriptive and quantitative analyses were performed using SPSS version 22.0 (SPSS, Inc., Chicago, IL, USA). The significance level was set at $p < 0.05$. A sample size of three for each group was estimated to achieve 0.80 power to detect a mean of paired differences of 50% of the strain, with a significance level of 0.05 using a two-sided paired $t$-test.\textsuperscript{20,21} Ligament length, strain, and stress during prono-supination motion in $1^\circ$ increments were compared by repeated-measures analysis of variance, followed, if necessary, by post-hoc analysis.

**Results**

The strain on the CB of the IOL was significantly lower than the strains on the PB and DB (Tables 1 and 2). In general, however, the strains on the PB and DB did not differ significantly.
When the strain on the IOL was plotted relative to the position of forearm rotation from pronation to supination (Figure 3), the overall strain on the IOL was lowest at maximum pronation, gradually increasing and peaking at early supination. Strain on the CB remained constant throughout forearm rotation, whereas strains on the PB and DB showed higher amplitudes and greater fluctuation.

Strain on the CB was lowest in pronation, gradually increased from 20° pronation to neutral position, reached a peak at 15° supination, and gradually decreased from 25° supination. Strain on the PB showed a more acute increase from full pronation to the neutral position. Strain on the PB also peaked at 15° supination and markedly decreased from 25° supination. Strain on the DB showed two peaks, at 5° pronation and 25° supination, and markedly decreased from 30° supination.

Regression analysis was performed to predict the relationship between ligament strain (independent variable) and the position of forearm rotation (dependent variable). All bands of the IOL showed a nonlinear complex relationship, making a linear regression model inapplicable. Ligament strain was therefore assessed using a polynomial regression model. Strain on the CB could be plotted with a second order polynomial model (quadratic expression). The relationships between forearm rotational position and ligament strain for the PB and DB were more difficult to interpret because the PB only fitted a third order (cubic expression) model, and the DB only fitted a fourth order (quartic expression) model. Figure 3 shows average ligament strains and the regression model of all bands during forearm rotation.

**Discussion**

Strain on the IOL is dynamic as it depends on forearm rotational position. The highest overall strain was observed in the neutral position, showing a gradual reduction as the forearm reached maximum pronation and supination. Strain on the CB maintained a constant trend throughout forearm rotation, whereas strains on the PB and DB showed higher amplitudes and greater fluctuation.

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**Table 1.** Ligament strain profiles of the proximal, central, and distal bands.

| Ligament strain profile | Proximal Band | Central Band | Distal Band | p-value |
|-------------------------|---------------|--------------|-------------|---------|
| Ligament strain (mm)    | 0.83 ± 0.47   | 0.08 ± 0.04  | 0.65 ± 0.23 | <0.001† |
| Minimum strain (μm)     | 0.009 ± 0.001 | 0.001 ± 0.002| 0.007 ± 0.001| <0.001† |
| Maximum strain (mm)     | 1.45 ± 0.09   | 0.13 ± 0.01  | 1.09 ± 0.06 | 0.067†  |

All values are reported as mean ± standard deviation.

† Analysis of variance test.

**Table 2.** Post-hoc analysis of comparative ligament strains on the proximal, central, and distal bands.

| Ligament strain profile | Post-hoc analysis |
|-------------------------|-------------------|
|                         | Central Band vs. Proximal Band | Central Band vs. Distal Band | Proximal Band vs. Distal Band |
| Ligament strain (mm)    | 0.001             | 0.001             | 0.818             |
| Minimum strain (μm)     | 0.045             | <0.001           | 0.032             |
| Maximum strain (mm)     | 0.001             | 0.005             | 0.721             |

† Tukey HSD.
positions but shorter in supination position.\(^5\) A radiological and anatomical study of variations in interosseous distances between the radius and ulna during the rotation of cadaver forearms found that neutral position provides the widest interosseous distance, indicating a taut position of the IOL.\(^{23}\) In this position, the level of radius curvature is maximal with respect to the ulna, and the interosseous crests are minimal and therefore further apart. By contrast, interosseous distances were narrower in both pronation and supination, indicating a lax position of the IOL.

Despite identification of the PB and DB, reconstruction of the CB is regarded as essential or longitudinal forearm instability. When forearm instability necessitate central band reconstruction, an inserted graft should not simply connect the apices of the radius and ulna. Rather, graft tensioning and placement are pivotal for successful results. Up until now, to which forearm position did the graft should be tensioned is still inconclusive. Strain on the CB was lowest at full pronation, with minimal changes until 20° pronation. If IOL reconstruction is performed to maximize graft tension, the graft should be tensioned in a position ranging from full to 20° pronation, when the distance between the radius and ulna is shortest. Nevertheless, the radius and ulna have been drilled during IOL reconstruction to assist with graft fixation. Tensioning while keeping the forearm in full pronation may, however, increase the likelihood of cross-union between the radius and ulna. Thus, 20° pronation may be sufficient for optimum graft tensioning while avoiding the risk of cross-union. Additionally, active rotation of the forearm should be prevented during early post-operative rehabilitation.

Previous studies have analyzed the bio-mechanical properties of the IOL in relation to the adjacent proximal and distal radioulnar joints.\(^2,3,5\) The present bio-mechanical study did not analyze the elbow and wrist joints concurrently, as these joints do not contribute significantly to strains on the IOL.\(^3,5\) Hence, the strains measured are those on the IOL alone, without any external influence.

From a clinical perspective, the findings of the current and previous\(^2,3\) studies enhance understanding of the bio-mechanical functions of the key osseo-ligamentous components of the forearm. These findings may improve procedures for IOL reconstruction and graft tensioning, as well as enable understanding of how to more precisely reconstruct this ligament in an anatomical manner. Modification of any one of these structures, by disease or surgery, may compromise the normal biomechanics and functions of other structures.

**Limitations**

This study had several limitations, including the small sample size and the use of elderly cadavers, limiting the generalizability of these findings. Additional specimens from younger aged individuals are needed to reach conclusive results. The time between death and fixation may also have altered our findings, as a longer postmortem period may increase the likelihood of tissue necrosis. However, despite these limitations, the experimental setup was designed for dynamic simulation. The forearm rotational axis, which had not been considered in previous studies,\(^2,3\) was considered when simulating forearm rotational movement in the present study.\(^18\) Use of the optical tracking system ensured highly accurate sub-millimeter measurements. Moreover, the data were recorded continuously, without any intervention, at a constant angular speed throughout simulation of forearm motion. One drawback of having highly accurate data, however, is the accumulation of enormous amounts of raw data, making noise reduction procedures strenuous and time consuming. The in situ strain was not measured in this study due to noise that might result from overcrowded fiducial markers when applied. The effect of muscle action was not a factor in these bio-mechanical experiments, as the aim of this study was an evaluation of the bio-mechanical properties of the IOL itself without any confounding effects due to muscle action.

**Conclusions**

Bio-mechanical analysis showed that the CB maintained a constant rotational strain throughout forearm rotation. Strain on the CB was significantly lower than strains on the PB and DB. By contrast, strains on the PB and DB varied, suggesting that their roles differ from those of the CB. The PB, CB, and DB function as an integrated osseo-ligamentous complex in the forearm. When CB reconstruction is needed, graft should be tensioned at 20° forearm pronation to gain optimum tension.

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**Declaration of conflicting interests**

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**Supplemental material**

Supplemental material for this article is available online.
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