The effect of excision of the radial head and metallic radial head replacement on the tension in the interosseous membrane

We measured the tension in the interosseous membrane in six cadaveric forearms using an \textit{in vitro} forearm testing system with the native radial head, after excision of the radial head and after metallic radial head replacement. The tension almost doubled after excision of the radial head during simulated rotation of the forearm \((p = 0.007)\). There was no significant difference in tension in the interosseous membrane between the native and radial head replacement states \((p = 0.09)\). Maximal tension occurred in neutral rotation with both the native and the replaced radial head, but in pronation if the radial head was excised. Under an increasing axial load and with the forearm in a fixed position, the rate of increase in tension in the interosseous membrane was greater when the radial head was excised than for the native radial head or replacement states \((p = 0.02)\). As there was no difference in tension between the native and radial head replacement states, a radial head replacement should provide a normal healing environment for the interosseous membrane after injury or following its reconstruction. Load sharing between the radius and ulna becomes normal after radial head Replacement. As excision of the radial head significantly increased the tension in the interosseous membrane it may potentially lead to its attritional failure over time.

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Fractures of the radial head are common; most are minimally displaced and successfully treated non-operatively, but surgical management may be required for more displaced fractures. Open reduction and internal fixation, albeit successful for simple displaced fractures, has been less reliable when treating fragmented and osteopenic fractures owing to a higher incidence of complications. The treatment of comminuted fractures of the radial head may include excision or arthroplasty; however, the optimal form of management is unknown.

In long-term studies, excision of the radial head has a good functional outcome in spite of a high incidence of the development of osteoarthritic changes and the potential for proximal radial migration. Good results have also been reported after the use of metallic replacement of the radial head. No randomised studies have compared the outcomes of excision of the radial head and replacement. Soft-tissue injuries of the elbow are commonly associated with comminuted fractures of the radial head, as damage to the interosseous membrane is common in even relatively low-energy fractures.

The purpose of this study was to examine the effect of excision of the radial head and radial head replacement on the biomechanics of the forearm compared with the native radial head in a cadaveric model. The magnitude of tension within the interosseous membrane and the position of maximum tension, and the characteristics of the tension were examined.

**Materials and Methods**
An \textit{in vitro} forearm motion simulator was developed in an attempt to recreate the biomechanical forces transmitted through the forearm in a physiological manner. The simulator was designed to produce axial loading of the forearm while simultaneously generating automated passive pronation and supination (Fig. 1). This device allowed unconstrained movement through the carpus, radius, ulna and elbow. The humeral mount permitted mediolateral translation, varus–valgus angulation and axial rotation. Multiple degrees of freedom were incorporated into the simulator to ensure adjustability for each specimen, and to allow loading of the forearm with minimal constraint.

The metacarpals were set in polymethyl methacrylate such that the third metacarpal was in line with the axis of the applied load, and the forearm was aligned with the applied load before similarly embedding the humerus.

Axial loading was applied through the metacarpals by a pneumatic actuator (FOD-094-S; Bimba, University Park, Illinois) and governed...
by a custom software controller using closed-loop feedback from a load cell (MBA 600; Futek, Irvine, California). Pronation and supination of the forearm were driven by a servomotor (Model SM2315-DT, Animatics, Santa Clara, California), with a cycle of rotation from pronation to supination and back to pronation in six seconds. In order to measure tension in the interosseous membrane, a custom load cell was constructed with a pair of strain gauges (120 Ω, 90° rosette; Vishay Micro-Measurements, Raleigh, North Carolina) fixed to a strip of spring steel 9.5 × 6.5 × 0.32 mm (Fig. 2). The load cell was woven over and under the fibres of the interosseous membrane, producing a bending axis via a three-point loading construct. After calibration, the load cell could quantify the tension in the interosseous membrane in real time under kinematic loading conditions.

Six cadaveric specimens (mean age 65 years (52 to 72)) were prepared for testing. The specimens were included only if there was no prior fracture or evidence of arthritis, based on CT scans. The arms were thawed at room temperature for 16 hours. The fingers were disarticulated at the metacarpophalangeal joints, and the metacarpals were stripped of all soft tissues. The thumb was disarticulated at the carpometacarpal joint. The tendinous insertions to the base of the metacarpals were maintained, as were the capsules of the wrist and carpal bones. All soft tissue was stripped off the humeral shaft, starting 8 cm above the elbow joint. Via a Thompson approach,9 a volar aperture was made to access the central band of the interosseous membrane, hinging the soft tissue at the ulna. The extensor digitorum communis was resected over the central band of the interosseous membrane. The remainder of the musculotendinous units were gently retracted to expose the interosseous membrane for a distance of 10 cm directly overlying its central portion. The proximal and distal portions of the interosseous membrane were divided to isolate the central band. Two 8 mm long parallel slits were made 4 mm apart in the central band parallel to the fibres of the interosseous membrane. Both ends of the load-sensing device were then inserted into the slits, thus weaving it into the central band of the membrane. Small holes at each end of the load cell were used to secure it to the membrane using 5/0 silk suture (Ethicon, San Antonio, Texas) (Fig. 2).

A Steinman pin was temporarily placed transversely through the metacarpals and the specimen was positioned with the wrist in neutral in all planes, and embedded in polymethyl methacrylate with the third metacarpal in line with the applied loading vector. The elbow was flexed to 90°, and the forearm and carpus aligned with the applied axial load. The humerus was also embedded in polymethyl methacrylate, and the limits of rotation of the forearm for each specimen were assessed manually and recorded by the servomotor. These terminal ranges of movement were then repeated precisely throughout all trials. Static muscle forces across the elbow were simulated with weights by suturing cables to the tendons of the brachialis, biceps and triceps using No. 2 Ethibond (Ethicon). A load of 2 kg was applied to the brachialis and biceps brachii, and 4 kg to the triceps.10 Muscle lines of action were maintained using an arrangement of adjustable pulleys.

A direct lateral approach to the radial head was performed by splitting the common extensor tendon and the underlying annular ligament. A small portion of the radial collateral ligament was released from the humerus to provide adequate exposure to resect and replace the radial head, but the humeral and ulnar attachments of the lateral ulnar collateral ligament were preserved. A small sagittal saw was used to make the osteotomy in the neck of the radius. The diameter and length of the native radial head was measured using callipers and the optimal size of...
arthroplasty of the radial head was selected. The canal of the radius was hand reamed and a trial stem and head were inserted (Evolve; Wright Medical Technology, Arlington, Tennessee). The annular ligament, radial collateral ligament and common extensor tendon split were repaired in layers using interrupted No. 2 Ethibond sutures (Ethicon).

Both active movement and static testing was conducted. For the active series, each arm was tested through a full range of pronation and supination for three cycles for each radial head state at 160 N. The tension in the interosseous membrane was measured continuously, with the third cycle being used for data analysis. The arm was then tested statically in neutral rotation. The load was applied at a rate of 8 N/s to 160 N. The forearm was tested with the native radial head, with the radial head excised, and with the radial head replaced. The tension recorded was plotted, and a line of best fit applied. The slope of this line of best fit was measured, and recorded as the rate of increase of tension in the interosseous membrane.

Statistical analysis. SPSS software was used (IBM Corp., Armonk, New York). One- and two-way analysis of variance (ANOVA) was used to calculate statistical significance, defined as p < 0.05, for the dependent variable of tension of the interosseous membrane. Repeatability was assessed by determining linear dependence using Pearson’s correlation coefficient of the interosseous membrane load sensor of sequential testing with the same test series.

Results
The system demonstrated good repeatability, with the load sensor having a Pearson’s correlation coefficient > 0.9, and SD of 0.7%.

The tension in the interosseous membrane increased after excision of the radial head during rotation of the forearm under a constant load, to almost double the values for the native or radial head arthroplasty (p = 0.007) (Fig. 3). There was no significant difference in tension between the native radial head and radial head arthroplasty states (p = 0.09). Maximal tension was measured in neutral rotation with both the native and the replaced radial head. When the radial head was excised, maximal tension in the interosseous membrane occurred with the forearm in pronation.

Under dynamic axial loading, the rate of increase in tension in the interosseous membrane was more rapid when the radial head was excised than in the native or arthroplasty states (p = 0.02) (Fig. 4, representative specimen), as well as the mean rate of increase for each radial head state (Fig. 5). When the radial head was excised, the rate of increase of tension occurred at a higher rate than in either the native or the radial head arthroplasty states (p = 0.02). However, following arthroplasty there was no difference in the rate of increase of tension in the interosseous membrane compared to the native radial head state (p = 0.78). The mean rate of increase in tension was lower than the rate of applied axial load (Fig. 4).

Discussion
The forearm simulator permitted physiological testing in a repeatable fashion. This enabled us to quantify the effect of axial loading and excision of the radial head and arthroplasty on tension in the interosseous membrane. The axial loads we applied were higher than in previous reports, in order to reflect the higher loads that can occur physiologically.

Direct instrumentation of the interosseous membrane with a calibrated strain gauge-based load cell has advantages over calculated tension. In most previous studies, the relationship between the interosseous membrane and radio-ulnar loading has been indirectly determined from strain gauges implanted in the osteotomised radius and ulna. Tension in the interosseous membrane has only been directly measured in one study, using an arthroscopically implantable force probe. However, although the
interosseous membrane was not violated in order to measure the tension, osteotomies of the radius and ulna were used, and no radial head arthroplasty group was included and therefore a direct comparison with our study is not possible.14

The position of maximal loading of the interosseous membrane has been found to occur in a variety of forearm rotations. Some authors have described the position of maximal tension to be in neutral rotation15,17,18 or supination.11,19 Others report that the interosseous membrane is isometric.20 In this study, the position of maximal tension in the interosseous membrane in an intact forearm was found to be in neutral. This was also found after radial head arthroplasty. With the radial head excised, the load on the interosseous membrane was maximal in pronation, which is in keeping with other studies.17

Excision of the radial head alters the radio-ulnar relationship, creating different tensions in the interosseous membrane than would be found in the intact or replaced radial head. Excision of the radial head resulted in an increase in tension in the interosseous membrane and the mean change was more than double the values seen with the radial head intact or replaced (Fig. 3).

It was found that the state of radial head had an influence on soft-tissue loading of the forearm. This increase in tension in the interosseous membrane following excision of the radial head may lead to attritional failure over time. The tension in the interosseous membrane does not change when the radial head is replaced, compared to the native radial head. This is clinically important, indicating that radial head replacement may allow the forearm to maintain normal biomechanics and load transfer between the radius and the ulna. If the interosseous membrane was damaged at the time of the injury that caused the fracture, it may be able to heal normally if the radial head is replaced. Given the challenges when treating chronic longitudinal radio-ulnar dissociation,21 this might eliminate a significant clinical complication.

The ability to load the forearm dynamically and measure the forces in the interosseous membrane has allowed us to characterise the forces under a changing axial load. There was no difference in the increase in tension in the interosseous membrane between the native and radial head replacement states. However, when the radial head was excised, the tension increased at a higher rate. The increased rate of rise in tension is what might be expected, but has not been previously reported. The mean rate of increase in tension within the interosseous membrane was less than the rate of applied axial load in all states of the radial head and the potential for load to be transferred via other soft tissue structures may explain this.

The response of the interosseous membrane to the state of the radial head has clinical implications. Higher tension in the interosseous membrane under constant axial loads, as well as greater increases in tension under changing axial loads, may affect the outcome in both the short and the long term. If treated with excision of the radial head, rehabilitation should be protective of the interosseous membrane, with low forces allowing the associated soft tissue injuries of the forearm to heal. The patient should be counselled that permanent restrictions might be appropriate because of the potential for attritional damage with delayed radioulnar longitudinal drift.5 Treatment with a radial head replacement restores the biomechanics of the forearm and therefore higher-intensity rehabilitation can be instituted soon after surgery. The patient would potentially be able to tolerate higher-impact activities in the long term, with a lower risk of attritional changes to the interosseous membrane.

This was an in vitro cadaveric study with elderly specimens, which has inherent limitations. Whether these results can be directly applied to younger patients in vivo remains to be confirmed. Although proximal and distal division of the interosseous membrane may be considered a weakness of the study, it was done while recognising that the central band is the most important portion of the interosseous membrane,17 and that it is a discrete structure amenable to the novel measurement techniques that were used.

Among the strengths of the study was the forearm simulator, which allowed a unique perspective on the load transfer characteristics of the forearm. The forearm was tested with minimal constraint while retaining its osseous integrity and an intact soft tissue envelope. Computer-controlled dynamic loading enabled accuracy of both axial loads and rotational speeds. A novel approach to the measurement of the tension in the interosseous membrane allowed dynamic and direct measurements of the forces transmitted.

In conclusion, this study demonstrated that excision of the radial head markedly increases loading on the interosseous membrane and alters load-sharing across the radius and ulna. However, insertion of a correctly sized metallic radial head replacement recreates near normal biomechanics of the forearm, with no change in the loading characteristics of the
interosseous membrane. This information may have a role in clinical decision making as well as rehabilitation of the forearm after fractures of the radial head.

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References