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ORIGINAL ARTICLE

Axial load transmission through the elbow during forearm rotation

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Background: Forearm rotation is closely associated with the axiorotational force transmission through the elbow joint. A technique has been developed to study the transmission of force across the radiocapitellar and ulnotrochlear joints during forearm rotation.
Methods: Ten human cadaveric upper limbs were prepared on a custom-designed apparatus that permits the application of extrinsic axial loads across an intact cadaveric elbow joint. A force-sensitive transducer was inserted into the elbow joint of each cadaver. A 160 N axial force was applied to the specimen during cyclic forearm rotation while the force, contact pressure, and contact area through the elbow joint were measured.
Results: The mean force across the radiocapitellar joint showed no significant difference between pronation and supination ($P = .3547$). The radiocapitellar joint showed significantly higher contact area ($P = .0001$) and lower contact pressure ($P = .0001$) in pronation than in supination. The mean values for contact pressure, area, and force across the ulnotrochlear joint were not significantly different between supination and pronation.
Conclusion: The contact pressure and contact area of the radiocapitellar joint in the cadaveric model changed according to forearm rotation while the force remained constant. The mean contact pressure of the radiocapitellar joint in pronation was significantly lower than that in supination because the force across it did not change significantly and its contact area decreased significantly. These findings may suggest that the pronated elbow can play an important role in protecting the radiocapitellar joint in high-impact activities like delivering punch in martial arts or falling on an outstretched arm.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Elbow; contact area; contact pressure; force; axial load; axiorotational force transmission; forearm rotation

This cadaver study was conducted under protocol number 10-008186, which was approved by the Mayo Clinic Biospecimen Committee on December 17, 2010.

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It has been reported in the literature that when the elbow is extended and axially loaded, the distribution of force is approximately 43% and 57% across the ulnotrochlear and radiocapitellar joints, respectively.[13] Forearm rotation has also been shown to have an effect on the distribution of axial load.[26] Of note, it is commonly observed that the forearm is

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pronated when a large axial load is applied to the elbow joint. Examples of this include a fall on an outstretched hand and delivery of a punch in boxing or martial arts like taekwondo and karate.[10,12,34]

Several studies have been performed on load transmission across the elbow joint as it relates to forearm rotation.[17-19,23] In 1988, a biomechanical study was performed by Morrey et al[26] using an axial load cell transducer implanted within the radial neck of 3 cadaveric elbows. They examined the force transmission through the full range of flexion and extension in both the pronated and supinated forearm.[26] This study demonstrated that the elbow experiences the greatest force transmission across the joint while the arm is in an extended position and that a larger radiocapitellar force is transmitted while the arm is pronated regardless of the degree of elbow flexion.[26] Subsequent to this study, Markolf et al demonstrated the importance of maintaining proper radius length when they examined radioulnar load sharing in the forearm[23] using externally mounted load cells. In a following study, these findings were corroborated when they examined load sharing in the wrist[24] after metallic radial head arthroplasty.[24] Another study by Fitzpatrick et al showed that when the forearm was pronated, a terrible triad injury pattern (fracture of radial head and coronoid with posterior dislocation) frequently occurred; however, when the forearm was supinated, a dislocation without associated fracture was more common.[7] More recently, comprehensive radiocapitellar axial load studies performed by Lanting et al have examined the effects of radial head excision, radial head implant length, and radial head diameter on interosseous membrane (IOM) tension,[17-19] radiocapitellar contact area,[18,19] pressure,[18,19] and force[19] with the elbow joint in 90° of flexion.[17-19] A 90° elbow flexion axial testing model was also used by Shannon et al to examine radiocapitellar contact areas in the context of different radial head prosthesis shapes.[32] Development in the area of radial axial load studies continues as Knowles et al have recently developed and validated a model for quantifying proximal radius loads by interposing an axial load transducer in the diaphysis of the proximal radius.[16] Although intraosseous force transducers can provide a wealth of valuable information, they do not have the ability to simultaneously directly quantitate joint areas and pressures.

Despite what has been learned about the biomechanics of forearm axial load transmission, at this time, contact pressure and contact area across the fully extended elbow joint during forearm rotation have not been well studied. In an effort to better understand the relationship between axial loading and forearm rotation, we hypothesize that the pronated elbow is more suitable for axial load transmission on the basis of the biomechanics associated with the contact pressure and area.

Materials and methods

All data are presented as the mean ± standard error of the mean.

Specimen preparation

Ten fresh frozen cadaveric limbs, from fingertip to mid humerus, of 8 men and 2 women were studied. The average age was 83 ± 2 years. The specimens were thawed at room temperature overnight before the experiment. Each specimen was examined clinically and radiographically. None of the specimens demonstrated a flexion contracture of >10°, a pronation-supination rotation arc <140°, or radiologic evidence of either arthritis or deformity under C-arm imaging. Specimens with ligament insufficiency detected by either gross examination or posterolateral rotatory drawer test were excluded. The skin and subcutaneous fat were removed from the mid humerus to 5 cm distal of the elbow joint. The biceps, brachialis, and triceps muscles were removed. The humeral origins of the flexor pronator and the extensor supinator muscles were spared. To insert the pressure transducer, the anterior capsule was excised, with care taken not to injure the collateral or annular ligaments. Any specimen with cartilage erosion to the subchondral bone was excluded; however, we included specimens that exhibited only shallow cartilage erosion with fibrillation or fissuring. The hand was amputated at the carpometacarpal joint. The proximal humerus and carpus were potted in polyurethane resin (Smooth-Cast 65D; Techno-Industrial Products, Hartland, WI, USA) in cylindrical metal sleeves parallel to the long axis for mounting in the testing machine.[3] A transverse olecranon osteotomy was made at the apex of the ulnar bare spot to facilitate placement of the pressure transducer.

Pressure transducer

A thin-film pressure transducer (5051; Tekscan, South Boston, MA, USA) with a saturation pressure of 8.3 MPa (1200 psi) was prepared by lamination with 2 thin layers of plastic and a reinforcing wire that served to protect it and prevent it from wrinkling in the joint. Four sutures were attached to the laminated sensor to facilitate its insertion into the joint. The pressure transducer was inserted into the elbow in the anterior to posterior direction until the end of the sensor reached the olecranon osteotomy line. The sensor was then adjusted to cover the entire joint, ensuring coverage of both the ulnohumeral and the radiocapitellar articulations, with the exception of the olecranon. The osteotomized olecranon was fixed back to the ulna with a plate (LCP Olecranon Plate 3.5 mm; AO Synthes, Oberdorf, Switzerland), and the sensor was secured by tying the 4 sutures to screw holes within the plate. The Tekscan sensor has been validated for rounded contact areas and used in previous studies of joint contact pressures for multiple areas of contact.[4,6,28] Each 5051 sensor has one 56×56 matrix (196 mm^2), comprising 1936 sensels (individual detection units of pressure sensor) located on conductive ink grids. The 5051 sensors were preconditioned and calibrated according to the manufacturer's recommendations. Tekscan data were captured at a frequency of 100 Hz.

Specimen mounting and testing

Each specimen was mounted onto a custom-designed apparatus that permits the application of extrinsic axial loads across an extended cadaveric elbow joint during cyclic and functional forearm rotation as seen in Figure 1. A force-sensitive transducer (5051, 1200 psi saturation pressure; Tekscan) was inserted into the elbow joint of each cadaver. The distal end and proximal end of the specimen were potted in the apparatus. The data acquisition handle (Tekscan