Techniques of Force and Pressure Measurement in the Small Joints of the Wrist

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Michael J. Schreck¹, Meghan Kelly¹, Colin D. Canham¹, and John C. Elfar¹

Abstract

Background: The alteration of forces across joints can result in instability and subsequent disability. Previous methods of force measurements such as pressure-sensitive films, load cells, and pressure-sensing transducers have been utilized to estimate biomechanical forces across joints and more recent studies have utilized a nondestructive method that allows for assessment of joint forces under ligamentous restraints. **Methods:** A comprehensive review of the literature was performed to explore the numerous biomechanical methods utilized to estimate intra-articular forces. **Results:** Methods of biomechanical force measurements in joints are reviewed. **Conclusions:** Methods such as pressure-sensitive films, load cells, and pressure-sensing transducers require significant intra-articular disruption and thus may result in inaccurate measurements, especially in small joints such as those within the wrist and hand. Non-destructive methods of joint force measurements either utilizing distraction-based joint reaction force methods or finite element analysis may offer a more accurate assessment; however, given their recent inception, further studies are needed to improve and validate their use.

Keywords: biomechanics, DRUJ, pressure-sensing films, joint forces, pressure transducers

Introduction

The forces acting across joints play important roles affecting stability that can be disrupted by injury, degenerative processes, and surgical interventions.^{21,22,26} Joints in the hand and wrist typically undergo smaller forces than larger joints given that they are non-weight bearing. However, the areas over which those forces are exerted are disproportionately smaller than the joint surfaces of the shoulder and elbow. Subsequently, altered biomechanics can result in instability and pain and lead to arthrosis,^{8,17,24,35} which is of clinical relevance given that basal joint arthritis has the second highest incidence of arthritis (knee being the most common).²³ Therefore, accurate methods of measuring these forces are important to understand articular pathology and predict how interventions will affect joint mechanics.

Biomechanical assessment of the forces acting across the joints of the wrist is particularly challenging due to their small size and the complex capsuloligamentous anatomy that imparts stability.^{26,28,35} Various methods of biomechanical evaluation of the small joints of the wrist are described,^{12,13,16,21,22} but there remains no true gold standard. The purpose of this review is to describe current techniques of force measurement across the small joints of the wrist, discuss their limitations, and examine potential areas for future development. Particular emphasis will be placed

on the distal radioulnar joint (DRUJ), as it has been widely studied with a variety of methods.^{6,12,13,16,21,22}

Any discussion about small joint biomechanics must make mention of relevant work from literature on the carpus, given that much of this early work has been proved critical in understanding wrist biomechanics. Works performed by Garcia-Elias et al have demonstrated the importance of carpal stability,^{10,11,15,18} its response to axial loading, and what occurs in pathological conditions such as Kienböck disease.¹⁵ These studies have highlighted the consequences of altered carpal stability and, as a result, have also highlighted the need for methods of direct measurements along individual small joint surfaces of the carpus and elsewhere that have subsequently been developed.

Pressure-Sensitive Films

Early methods of evaluation of the DRUJ involved the use of thin (0.13 mm) pressure-sensitive films. This technique

¹University of Rochester, NY, USA

Corresponding Author:

John C. Elfar, Associate Professor, Department of Orthopaedic Surgery, University of Rochester, 601 Elmwood Avenue, Box 665, Rochester, NY 14642, USA.

Email: openelfar@gmail.com

Figure 1. Setup for pressure film measurements of distal radioulnar joint following radial-shortening and ulnar-lengthening osteotomy.

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involves placement of the film between the surfaces at which a contact pressure measurement is desired. When pressure is applied, a colored stain or digital image of varying intensity is produced, which changes in density corresponding to the pressure intensity. The film is then analyzed using specific software in order to quantify the pressure and measure the area over which it is applied.^{2,32}

Werner and colleagues utilize this method when examining the effects of ulnar-lengthening or radial-shortening osteotomy on the DRUJ (Figure 1).³² The film is trimmed to fit the shape of the joint and placed within the sigmoid notch. After loading, the film is visually inspected to ensure that there is no evidence of oversaturation; otherwise, it is replaced with a film of lower sensitivity. The resultant colored print is then converted to gray scale for video-assisted

image processing. The pressure measurements were repeated at least 4 times to ensure a clean result without soft tissue interference; however, only one is utilized for video processing. Signal intensity is determined by calibration measurements with known pressures.

The use of pressure-sensitive film for measuring joint contact pressures has considerable limitations.^{2,19} The film can be difficult to contour appropriately to a relatively small curved joint, such as the DRUJ, and adjustments in the film, such as slitting, can result in overlap of the film and unreliable pressure measurements.³² Furthermore, Bachus et al noted inaccuracies in the measured area over which the load is applied, particularly in the Fuji film (Fuji Photo Film Co Ltd, Tokyo, Japan), as well as the measured pressure, when compared with a known standard.² While the manufacturer notes an accuracy of $\pm 10\%$ when utilizing a densitometer, this can be particularly concerning when measuring changes that are subtle, such as those reported in the DRUJ after a radial-shortening osteotomy, thus making results difficult to interpret.³² Finally, Liao et al noted that interposition of a 0.2-mm film to measure contact forces at the tibiofemoral joint changed the contact characteristics between the tibia and femur, leading to inaccurate measurements.¹⁹ The measurement errors seen in a large joint such as the knee could be magnified in the very small joints of the hand/wrist, where the relative contact disruptions would be much greater.

Instrumented Prostheses

Gordon et al¹² measured the force across the DRUJ using an instrumented ulnar head replacement system with strain gauges to measure bending moments. They removed the distal 5 cm of the ulna and cemented the instrumented distal ulna replacement into place. The arms were mounted in an upper extremity joint simulator. Simulated loading of the tendons of the biceps, triceps, pronator quadratus, supinator, and pronator teres muscles is accomplished using suture lines routed through a pulley alignment system attached to computer-controlled pneumatic actuators. Various muscle loads were applied, and joint reaction force (JRF) across the DRUJ is measured in positions of pronation, neutral, and supination (Figures 2 and 3). They used this method to demonstrate that the JRF increased with increasing muscle loading but that the relationship is not strictly linear. The biceps is found to exert the greatest effect on the magnitude of the JRF when compared with the other muscles tested, and this influence is greatest in forearm pronation.¹²

This study offered valuable new data correlating DRUJ JRF with loading of muscles of the upper extremity; however, it has its limitations. The shape of the native ulnar head varies from that of a prosthesis; contact forces between the sigmoid notch and ulnar prosthesis are therefore likely

Figure 2. In vitro upper extremity joint simulator utilizing pneumatic actuators and a pulley system to apply muscular loads at various forearm positions.

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not the same as in the native joint. In addition, the use of a single suture line to simulate the loading of muscles with broad insertions may have altered the physiologic pull of the muscles.¹² Finally, extensive soft tissue dissection is required, resulting in the disruption of numerous soft tissue stabilizers about the DRUJ. Disruption of these structures has been shown to alter force transmission across the DRUJ.^{20,31}

Pressure-Sensitive Transducers

Pressure transducers have also been used in the measurement of DRUJ pressure, which, unlike pressure sensor films, offer dynamic pressure measurements within the joint. This allows investigators to examine the effects of pronation and supination on joint mechanics as evidenced by the work of Ishii and colleagues,¹⁶ who utilized the Tekscan system (Tekscan, Inc, Boston, Massachusetts). The dorsal capsule of the DRUJ is incised to allow placement of the pressure film within the articulation of the distal radius and ulna. Repair of the flexor and extensor retinaculum is performed

Figure 3. Preparation of specimen with the ulnar replacement system to be used with joint simulator as seen in Figure 2.

Source. Reprinted with permission from Gordon et al.¹²

Note. ETD = electromagnetic tracking device.

after placement of the sensor. Weights of varying magnitudes were suspended from the extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), extensor carpi ulnaris (ECU), flexor carpi radialis (FCR), and flexor carpi ulnaris (FCU) and data are recorded (Figure 4). The study demonstrated that as an axial load is applied to the forearm in neutral rotation, the area of contact between the ulnar head and sigmoid notch increased. In addition, it is noted that in pronation, pressure is concentrated in the dorsal portion of the sigmoid notch, and that in supination pressure is primarily located in the palmar portion of the sigmoid notch.¹⁶

A similar method is utilized by Nishiwaki et al in which pressure transducers were placed into the DRUJ to examine changes in pressure associated with ulnar shortening in torn and intact states of the triangular fibrocartilage complex.²¹ The system used (I-SCAN 10 × 10; Nitta Corporation,

Figure 4. Experimental setup for utilizing pressure-sensing transducers, in concert with measurements from an electromagnetic tracking device.

Source. Reprinted with permission from Ishii et al.¹⁶

Osaka, Japan) is composed of a sensor, computer interface, and software. Each sensor is made up 2 polyester sheets that contain patterns of electrical conductor and are typically 0.1 mm thick. The sheets are bonded together, and a layer of semiconductive ink separates the patterns of conductor. Each point at which the conductor on one sheet crosses the conductor on the other sheet produces a sensing element. As force is applied to the sensor, and the ink layer is compressed, which produces a change in electrical resistance across the sensing element. Computer software then relates the change in resistance to the force applied. This method offers spatial resolution in pressure measurements within the joint.³³

The experiment by Nishiwaki et al required the excision of all skin, subcutaneous tissues, and muscles proximal to the wrist. The tendons of the ECRL, ECRB, ECU, FCR, FCU, biceps, pronator teres, supinator, and pronator quadratus were sutured to strings to simulate muscle contraction. Pressure sensors were inserted into the DRUJ to record pressure distribution; removal of the DRUJ capsule and the

Figure 5. Example of pressure-sensing transducers to determine baseline pressure measurements in distal radioulnar joint.

Source. Reprinted with permission from Nishiwaki et al.²¹

distal membranous portions of the interosseous membrane (IOM) is required for their insertion. Baseline pressure measurements were taken in various positions of forearm rotation, followed by the application of a load of 20 N to the strings attached to the various tendon units (Figure 5). Testing is then repeated after sectioning of either the palmar or dorsal portion of the radioulnar ligament. The researchers found that with progressive ulnar shortening, peak pressure on the DRUJ gradually increased. Sectioning of the radioulnar ligaments led to smaller increases in peak pressure after ulnar shortening. Although pressure transducer technology allows for spatial mapping of pressure applied to an area, it suffers from the same limitations of film measurement, most notably the disruptive interposition of the measuring element.²¹

Load Cells

Load cells are used to measure forces acting at the distal radius and ulna. A load cell produces an electrical output

Figure 6. Measurements of forces can be determined by changes in electrical magnitude as detected by load cells. Source. Reprinted with permission from Greenberg et al.¹³ Note. FCR = flexor carpi radialis.

that changes in magnitude when a force is applied. It is made up of an elastic element connected to strain gauges. The strain gauge is typically made up of an insulator and metallic foil, which acts as a resistor. Application of force causes the elastic element to which the gauge is bonded to deform, which is measured as strain. The gauges measure the strain that is generated as a change in resistance, which is then digitally converted to a force measurement.⁴ Greenberg and his colleagues examined the effect of the distal metaphyseal ulnar-shortening osteotomy on axial ulnocarpal forces, as well as transverse forces across the DRUJ using load cells mounted on the distal radius and distal ulna.¹³ In a fresh-frozen cadaver model, with retention of IOM structures and tendons, testing included a wrist motion simulator with 6 degrees of freedom and a load cell placed on the distal radius and distal ulna. The distal IOM is sectioned to the level of the sigmoid notch, such that the load cell measurements would reflect the forces applied to the distal radius and ulna. Wrist motion is measured with an electromagnetic sensor, and load measurements were taken with the wrists moved through a series of motions by pulling on wrist extensors (ECU, ECRB, ECRL) and flexors

(FCR, FCU). After distal metaphyseal ulnar-shortening osteotomy is performed, force is again measured and compared with preosteotomy values (Figure 6). The study demonstrated that significant decreases in ulnar load were achieved with distal metaphyseal ulnar-shortening osteotomy in static positions. Peak loads were also decreased with dynamic wrist motion. Furthermore, there is no statistically significant change in transverse force across the DRUJ after osteotomy.¹³

Limitations of Current Techniques

While insertion of pressure- and force-sensing devices into joints allows for direct measurements of pressure and force across them, these methods have considerable limitations. Implanting these devices is invasive and requires disruption of the capsuloligamentous complexes overlying the joint of interest. Previous studies have demonstrated that 80% of stability at the DRUJ is conferred by the palmar and dorsal radioulnar ligaments, with articular contact between the radius and ulna contributing 20%.²⁷ It has also been shown that the DRUJ joint capsule plays an important stabilizing role and significant instability results when it is sectioned.³¹ Disruption of these important soft tissue stabilizers is required to insert intra-articular devices and likely results in instability and altered force transmission across the joint.³¹ Furthermore, the distal IOM acts as a secondary stabilizer of the DRUJ.²⁰ In addition to disrupting joint stability, these methods also alter normal joint mechanics.¹⁹ The work of Liao et al demonstrated that the interposition of a small film at the tibiofemoral joint altered joint contact characteristics.¹⁹ Ideally, methods of measuring forces across joints would allow for the preservation of all periarticular stabilizing structures and maintain native joint mechanics, in order to obtain measurements as accurately as possible.

Nondestructive Methods of Force Measurement

Few authors have examined noninvasive methods of measuring forces across joints. A noninvasive, nondestructive method for the measurement of JRF was developed by Yang et al, for measurement across the knee joint after tibial lengthening in a rabbit model.³⁴ The theory behind the set of experiments performed by Yang's group is that the JRF is determined by the passive tension-length characteristics of the soft tissues that cross a joint. A resting tension exists, and as a joint is distracted, there is a point at which the JRF is overcome and the joint surfaces will begin to separate. In a plot of the distracting force versus joint displacement, the point just before the surfaces separate when the JRF is overcome is represented by the inflection point on the curve. This inflection point is equivalent to the JRF (Figure 7). The researchers developed a bilateral distracter, similar to an

Figure 7. Noninvasive method of determining the joint reaction force (JRF) in the rabbit knee joint. The inflection point is the point at which the distraction force overcomes the resting tension of the soft tissues and thus represents joint reaction force.

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Figure 8. Schematic diagram of joint reaction force measurements in the knee using 2 force sensors and an extensometer to determine distraction force and joint distraction displacement.

Source. Reprinted with permission from Yang et al.³⁴

external fixator, which is applied across the rabbit knee. Force sensors were incorporated into the sides of the bilateral distractor to measure the force along the distractor rod. An extensometer is constructed to measure joint displacement. This technique is developed and used to assess the change in knee JRF after a tibial-lengthening procedure (Figure 8). Measurements of distraction and displacement

obtained at various time points were used to determine the JRF, which is compared between the lengthened and control subjects. The results of the study were in agreement with the researchers' theory and demonstrated that the knee JRF is significantly elevated when compared with control after a tibial-lengthening procedure. This method did not require any significant dissection of the periarticular soft tissues. However, it is limited in that it is somewhat invasive and would require anesthesia to perform on living subjects.

Canham et al studied DRUJ JRF by modifying the method of Yang.⁶ Using a fresh-frozen cadaver model, threaded Steinmann pins were placed percutaneously into this distal radius and ulna collinear to one another, and transverse to the DRUJ. The radial pin was threaded into a tensile load cell (Futek, Irvine, California). Specimens were mounted on a tensile testing machine (MTS Insight 100; MTS Systems, Eden Prairie, Minnesota) using a custom apparatus. An extensometer is placed on each pin for precise measurement of displacement (Figure 9). The DRUJ is then distracted while force and displacement were simultaneously measured. A force versus displacement curve is generated, and the JRF is determined from the inflection point noted, calculated from the force versus displacement plot generated (Figure 10). The researchers found a mean JRF of 7.5 N (3.5-11.0 N) in the cadaver specimens. They went on to characterize the effects of diaphyseal versus metaphyseal techniques and found that diaphyseal shortening led to significant increases in the native JRFs.⁵ The advantages of this method included preservation of all supporting soft tissues and a high degree of precise and

Figure 9. The noninvasive method of measuring joint reaction force applied to the distal radioulnar joint utilizing percutaneous placement of Steinmann pins in the radius and ulna.

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Note. MTS = tensile testing machine (MTS Insight 100, MTS Systems, Eden Prairie, Minnesota).

Figure 10. Example of force versus distraction displacement curve to establish joint reaction force in the distal radioulnar joint. A best-fit polynomial for the curve was applied to determine the force at the inflection point.

Source. Reprinted with permission from Canham et al.⁶

accurate measurements. Furthermore, the relevance of JRF measurement is 2-fold: (1) In small joints, where interpositional measurements are impossible because of their destructive nature, a true assessment of JRF has never been fully realized; and (2) smaller joints of the hand with their inherent decreased joint thickness may be more susceptible to cartilage injury and altered force mechanics than larger,

Figure 11. Example of the use for computer modelling as another non-invasive method to measure joint forces using high-resolution quantitative computer tomography. (a) Full distal radius model with force vectors and (b) small cross sectional region measured in clinical practice.

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thicker joints. On the contrary, their method is considerably limited by the fact that their technique could not evaluate the effects of DRUJ loading and forearm rotation on JRF. In addition, the invasive nature of pin placement prevents the use of this method in a clinical setting without anesthesia.

Finite Element Analysis

Finite element analysis and computer modeling techniques represent a noninvasive method to study forces and kinematics in the small joints. Through the use of high-resolution quantitative computed tomography (HRqCT), the hand/wrist can be scanned in vivo, and a highly detailed 3-dimensional digital model of the patient's distal radius and ulna as well as carpal bones can be constructed.^{7,9} Such techniques have been used to examine bone loading in the distal radius (Figures 11 and 12), carpal kinematics, load transmission after division of the transverse carpal ligament (Figures 13 and 14), and the stability of various fixation techniques for distal radius fracture and scaphoid fracture.^{7,14,25,30} The pathomechanics of rheumatoid arthritis of the wrist have also been examined with this method.³ Soft tissue structures are left entirely undisturbed using computer models, and forces can be studied in vivo, rather than on cadaver specimens. Limitations to this method include issues with accuracy, found by Varga et al in a study using computer modeling to examine scaphoid contact pressures in varying hand positions.²⁹ In addition, validation of computer models using previously established methods can

Figure 12. Conversion of computer model to finite element analysis to determine local distribution of strain energy (SED) with the application of 100 N compressive load. As in Figure 11 (a) full distal radius model and (b) clinical model. Source. Reprinted with permission from Christen et al.⁷

Figure 13. A 3-dimensional finite element model of the skeleton-ligament complex developed from a computed tomographic image. Source. Reprinted with permission from Guo et al.¹⁴

Figure 14. Use of a 3-dimensional finite element model to determine contact stress distribution of the distal radius under 100 N of compressive load. Source. Reprinted with permission from Guo et al.¹⁴ Note. TCL = transverse carpal ligament.

prove challenging,¹ and these models generally assume a uniform distribution of materials within each tissue type which may not occur in vivo. Anderson et al noted that difficulties in establishing the base geometry and modeling of the articular surfaces based on a cadaver specimen for a finite element model examining radiocarpal joint stresses confounded validation.¹ Ultimately, these models may also represent an oversimplification of complex articular biomechanics.⁷

Conclusion

The hand surgery literature has focused largely on invasive methods of measuring forces in the small joints of the wrist/hand. Pressure-sensitive film, transducers, and load cells have all been used and require considerable soft tissue dissection, as well as interposition of components, in order to obtain data. Noninvasive methods of JRF measurements and finite element analysis offer attractive alternatives given that these methods account for important biomechanical contributions from the soft tissue attachments adjacent to the small joints. However, these methods are still being refined and currently have considerable limitations. Further research is needed to improve and validate noninvasive methods for the measurement of forces in the small joints of the wrist/hand. Such techniques would likely allow for a more accurate assessment of the biomechanics of the small joints of the upper extremity.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

This article does not contain any studies with human or animals subjects.

Statement of Informed Consent

Informed consent was obtained when necessary.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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