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Short communication

Study of intraarticular pressures in the elbow joints

Xavier Casanova Canals [a,b], Angel Ferreres Claramunt [c], Montserrat Del Valle Jou [d], Miguel Pérez Abad [e], Diana Noriego Muñoz [f,*], Alfonso Rodríguez Baeza [g]

[a] Causse Clinic, C/Carrer del Carme, 131, 17004 Girona, Girona, Spain
[b] Clinica Salus Infirmorum, Passeig de Mossèn Lluís Constans, 130, 17820 Banyoles, Girona, Spain
[c] Institut Kaplan, Passeig de la Bonanova, 9, 08022 Barcelona, Spain
[d] Fundació Hospital de L'Esperit Sant, Avenida Mossèn Pons i Rabadà, s/n, 08923 Santa Coloma de Gramenet, Barcelona, Spain
[e] Althaia Xarxa Assistencial Universitaria de Manresa, C/ Dr. Joan Soler, 1-3, 08243 Manresa, Barcelona, Spain
[f] Hospital Universitari Dr Josep Trueta de Girona, Av França s/n, 17002, Girona, Girona, Spain
[g] Facultat de medicina, Universitat Autònoma de Barcelona, Edifici M, Avinguda de Can Domènech, 08193 Bellaterra (Cerdanyola del Vallès), Barcelona, Spain

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ABSTRACT

The purpose of this study was to describe pressure originating in the six elbow articular compartments after muscular contractions. Ten cryopreserved cadaveric arms were dissected and the insertional tendons and capsuloligamentous tissues were preserved. The specimens were placed in a custom-made device. Elbow position was established at 90° flexion with the forearm in a neutral position and the wrist extended at 0°. Tekscan sensors sere used for measuring intraarticular pressures.

Without loading the elbow, the humeroradial joint received the lowest pressure, and, among the humeroulnar joints, the highest pressure was found in the anterolateral compartment. After loading the epitrochlear muscles to the maximum (5.0 kg), the pressure increased in the anteromedial joint (0.6 kg to 3.3 kg) and decreased in the posteromedial and anterolateral joints (4.2 kg to 0.3 kg and 4.2 kg to 0.9 kg, respectively). After the same loading in the epicondylar muscles, the pressure increased in the anterolateral and humeroradial joints (4.2 kg to 8.2 kg and 0.2 kg to 1.0 kg respectively), but decreased in the posterolateral joint (3.4 kg to 1.0 kg). The pressure distribution patterns among the humeroulnar compartments depend on the muscle geometries and their origins. Understanding these patterns can be useful in applying physiotherapeutic treatments for reinforcement of different muscular groups in order to decrease pressure in certain articular compartments.

1. Introduction

Elbow flexion is useful for sufficient elbow function and hand movement during daily activities. In this sense, it is important to understand the effects of the muscles that cross these joints and the distribution of pressures within them. Many biomechanical studies have reported the distribution of pressures in the elbow (Ahmed and Burke, 1983; Amis et al., 1980; Anderson, 1978; Bachus et al., 2006; Bernstein et al., 2000; Bryce and Armstrong, 2008; Chantelot et al., 1998; Chantelot et al., 2008; Eckstein et al., 1994; Halls and Travill, 1964; Willing et al., 2013; Donkers et al., 1993) with the elbow extended (Chantelot et al., 2008; Diab et al., 2005; Halls and Travill, 1964; Tillmann, 1978) but have only considered the humeroradial joint. (Diab et al., 2005; Morrey et al., 1988; Ofuchi et al., 2001; Sahu et al., 2017) Moreover, studies considering the humeroulnar joint (Chantelot et al., 2008; Goel et al., 1982; Halls and Travill, 1964) are difficult to compare because of differences in the methodologies (Ahmed and Burke, 1983; Diab et al., 2005; Eckstein et al., 1994; Eckstein et al., 1993; Goel et al., 1982; Morrey et al., 1988; Ofuchi et al., 2001; Paredes-Madrid et al., 2011; Willing et al., 2013).

The aim of this study was to evaluate the articular elbow pressures by reproducing the muscle contraction with different loads, at 90° flexion. We recorded pressure in six compartments of the elbow joint and demonstrated the pressure changes inside them, depending on moment arms generated by loading tendons. Elucidating the articular pressure distribution pattern of each muscle can be useful for future clinical and therapeutic protocols that aim to modify pressure loads in specific ulnohumeral/radiohumeral joint compartments such as radial head prosthesis or total elbow replacements in post-traumatic articular elbow disorders.

* Corresponding author.
E-mail addresses: angelferreres@institut-kaplan.com (A. Ferreres Claramunt), enfira@gmail.com, dnoriego.girona.ics@gencat.cat (D. Noriego Muñoz), Alfonso.Rodriguez@uab.cat (A. Rodríguez Baeza).

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2. Materials and methods

2.1. Preparation of specimens

We analyzed ten fresh-frozen (−40 °C) cadaveric upper extremities (average age: 77.3 years; 6 male and 4 female; 4 left and 6 right) without cartilage injuries (Annex 1). They were transected at the humeral midshaft and thawed overnight at room temperature. All elbow ligaments, the interosseous membrane, the whole hand, and the wrist were preserved. The distal tendons of the tested muscles were cut at least 5 cm proximal to their insertion at the wrist or hand.

2.1.1. Muscles tested

- Epitrochlear group: flexor carpi radialis (mFCR), flexor digitorum superficialis (mFDS), flexor carpi ulnaris (mFCU), pronator teres (mPT)
- Epicondylar group: extensor carpi ulnaris (mECU), extensor digitorum (mED), extensor carpi radialis brevis (mECRB), extensor carpi radialis longus (mECRL), brachioradialis (mBR).

Using staples, the distal tendons were attached to pulling ropes that were passed through the epicondylar and epitrochlear tunnels to reproduce the muscle traction vectors (Fig. 1).

2.2. Instrumentation

The specimens were individually placed in a custom-made device at 90° flexion, neutral pronosupination, and 0° flexo-extension of the wrist.

Flexion was achieved by mimicking the brachialis function, which involved passing a rope through the bone tunnel made in the ulnar insertion and fixing it to a conventional dynamometer. Neutral pronosupination was maintained with a handmade device that allowed varus-valgus displacement and unconstrained axial forearm translation during muscle loading (Ekenstam et al., 1984; Hotchkiss et al., 1989; Markolf et al., 1998; Morrey et al., 1991; Rabinowitz et al., 1984). Finally, wrist extension was achieved by introducing a 2.5 mm pin from the third metacarpal to the radius (Fig. 1).

Intra-articular pressure measurements were made with the TekScan Flexiforce B201 force-sensitive sensor (Medium Inc., South Boston, MA, USA). A new sensor was used for each specimen and was inserted into the joint through anterior and posterior capsulotomies. The sensors were calibrated according to the manufacturer's protocol (Fig. 1). Six intra-articular compartments were studied individually: humeroradial (HR), proximal radioulnar (PRU), medial and lateral anterior humeroulnar (MA and LA, respectively), and medial and lateral posterior humeroulnar (MP and LP, respectively).

The authors ensured that the sensor covered the contact area of the muscle as described in previous studies (Chantelot et al., 2008; Goel et al., 1982; Ofuchi et al., 2001; Willing et al., 2013). In the HR compartment, the sensor was placed in the medial half of the joint (Chantelot et al., 2008; Ofuchi et al., 2001; Willing et al., 2013).

After passing across the humeral tunnels, the ropes that were stapled to the distal tendons were redirected through pulleys and individually loaded with 0, 1, 3 and 5 kg. Pressure values were obtained for each weight, joint and tendon. We measured the joints and tendons in the following sequences: HR, PRU, LA, MA, MP, LP and mFCR, mFDS, mFCU, mECU, mEC, mECRB, mECRL, mBR, and mPT.

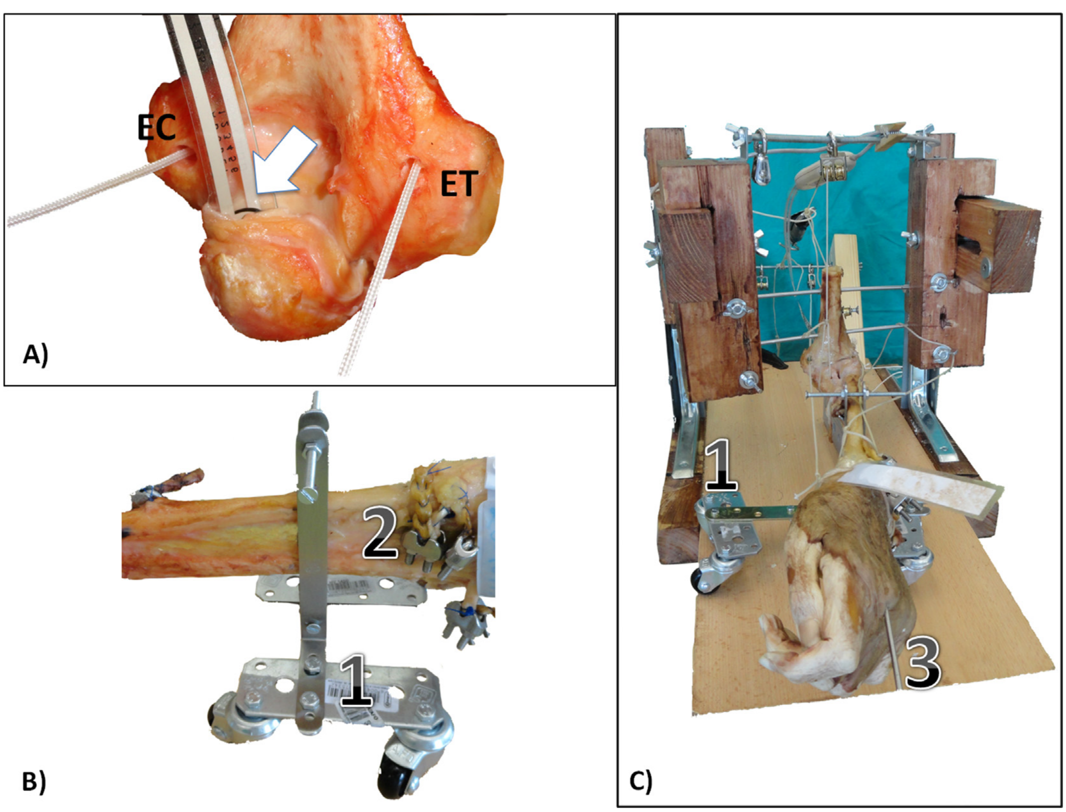

Fig. 1. (A) The epicondylar (EC) and epitrochlear (ET) osseous tunnels have been prepared for leading traction strings in order to reproduce main insertion of each tested tendon. White arrow: Pressure sensor device. A transolecranian 2 mm tunnel has been prepared for sensor stabilization in posterior compartments, if needed. (B and C) Subjecting elbow device and other details. (1) Neutral pronosupination is maintained with a gadget at the midpoint between Brachioradialis and Pronator Teres insertions. This system do not interfere the dynamic relationship between radius and ulna through interosseous membrane and allows varus/valgus displacements during tendon loading. (2) Tendon staple system. (3) Steinmann pin to block the wrist.

2.3. Statistical analyses

We compared the variation of pressure in each compartment under the different loads and stratified by muscles using the Mann-Whitney-Wilcoxon test. We used the Wilcoxon signed-rank test to compare the variation of pressure between compartments under the same load stratified by muscles. The calibration of the sensors and its reliability was tested using a double bivariate analysis. The threshold of significance was set at $p \leq 0.05$ (Software SAS v 9.3).

3. Results

Without loading, the highest pressures were measured in the LA joint (0–3.22 kg/f/cm^2). At a load of 5 kg, the highest pressures were observed at the MA joint (0–5.35 kg/f/cm^2) for the epitrochlear group and at the LA (0.09–6.95 kg/f/cm^2) and HR (0.31–3.04 kg/f/cm^2) joints for the epicondylar group (Table 1).

3.1. Muscles of epitrochlear group

When loading, a varus moment produced pressure changes in MA, MP, LA, and HR compartments (Fig. 2).

3.1.1. Pressure comparisons inside each articular compartment

A pressure increase in the MA and decreases in the MP and LA compartments were statistically significant for the mFCU, mFCR, and mPT, but not for the mFDS (although a similar trend was seen (Annex 2).

Progressive loading from 0 to 3 kg resulted in statistically significant increases in the HR pressure compartment for all muscles

Table 1
Median pressures for 0 and 5 kg of load (Kgf/cm^2). The joints had statistically significant variation after loading at máximum tendons are shown in red boxes.

EPICONDYLAR GROUP																				
JOINT	HR				LA				MA				MP				LP			
TENDON	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD
ECU	0,02	0,15	1,16	0,80	1,84	1,06	3,75	1,86	0,30	0,88	0,11	0,62	1,45	1,50	1,45	1,42	1,64	0,91	0,45	0,60
ED	0,02	0,10	1,52	0,86	1,84	0,98	3,09	2,00	0,30	0,75	0,18	0,65	1,20	1,56	1,14	1,56	1,68	1,37	0,50	1,78
ECRB	0,09	0,10	2,36	0,94	1,84	0,96	2,86	1,71	0,34	0,87	0,30	0,97	1,27	1,59	1,20	1,53	1,55	1,03	0,55	0,44
ECRL	0,02	0,10	2,11	0,81	1,89	0,96	3,02	1,85	0,34	0,75	0,23	0,65	1,16	1,60	1,14	1,75	1,48	0,95	0,48	0,43
BR	0,09	0,10	1,34	0,88	1,84	1,02	2,07	1,72	0,30	0,82	0,32	0,72	1,36	1,56	0,98	1,31	1,55	1,00	0,43	0,38

EPITROCHLEAR GROUP																				
JOINT	HR				LA				MA				MP				LP			
TENDON	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD	0 Kg	SD	5 Kg	SD
FCR	0,09	0,31	0,68	0,39	1,98	1,09	0,50	0,82	0,36	1,00	1,68	1,65	1,57	1,40	0,07	1,11	1,48	0,94	1,55	0,90
FDS	0,09	0,10	0,57	0,39	2,00	1,06	0,57	1,23	0,34	0,94	1,55	1,64	1,36	1,50	0,05	1,05	1,48	0,89	1,34	0,90
FCU	0,09	0,10	0,34	0,41	1,95	0,98	0,39	0,71	0,30	0,84	1,66	1,50	1,25	1,49	0,32	1,07	1,45	0,95	1,45	0,95
PT	0,07	0,10	0,30	0,33	1,84	1,00	0,25	0,32	0,25	0,83	1,20	1,57	1,16	1,54	0,11	1,27	1,45	0,88	0,86	0,80

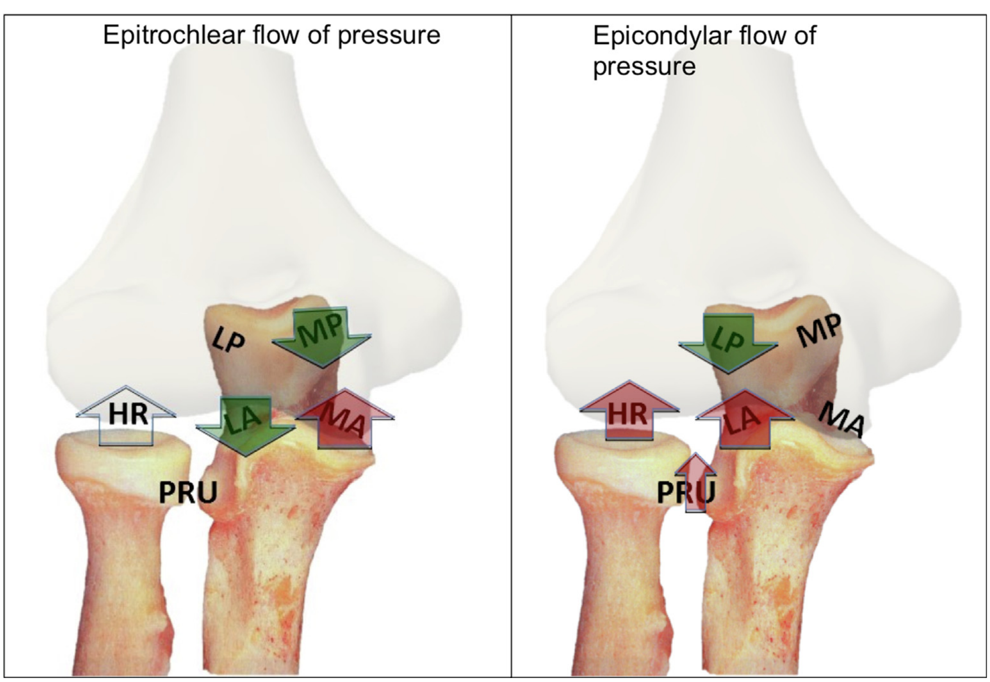

Fig. 2. Schematic elbow compartments. (a) Loading epitrochlear group, the pressure increase in the MA compartment and decrease in the MP and LA compartments. In the HR joint it increase with low loads but this effect disappears at high loads. (b) Loading epicondylar group, the pressure increase in the HR, LA and PRU compartments (smaller arrow for PRU compartment due to its low effect) and decrease in the LP compartment.

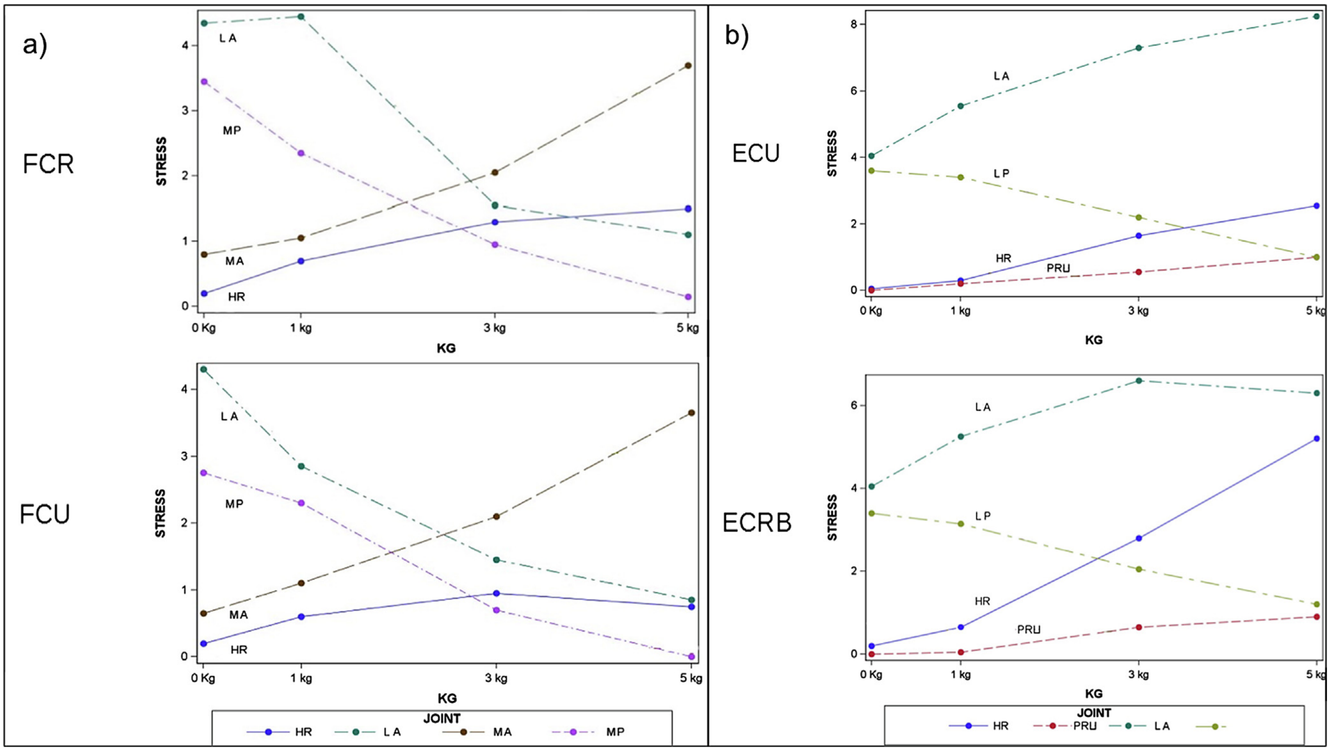

Fig. 3. Graphic of compartmental pressure distribution pattern (median lineal graphics) in epitrochlear group (FCR and FCU muscles are taken as an example). In epicondylar group (ECU and ECRB muscles are taken as an example). Only the compartments that showed statistically significant differences are shown. Stress units are expressed in Kgf/cm^2.

of this group (except between 0 and 1 kg for mFCR); however, these increases were not observed at higher loads (3–5 kg).

3.1.2. Comparison of articular compartments for each load (compartments with statistically significant variation of pressures: MA and HR with MP and LA)

We compared pressures between MA and MP and LA for each load. All comparisons between 0 and 5 kg showed statistical significance; this was not observed for loads of 1 and 3 kg (Fig. 3). There was a flow of pressure from MP and LA to MA.

A statistically significant pressure increase in HR corresponded to a decrease in pressure in MP and LA joints. The converging point was found at a load of 3 kg and remained approximately the same at a load of 5 kg. No statistical significance was found between HR and MP or HR and LA at loads of 3 and 5 kg.

3.1.3. Muscles of epicondylar group

When loading, a valgus moment produced pressure changes in LA, LP, HR and PRU (Fig. 2).

3.1.4. Pressure comparisons inside each articular compartment

Statistically significant pressure increases in the LA, HR, and PRU compartments (except for mECRL at 3–5 kg) and a statistically significant decrease in the LP (except for mED at 0–1 kg) were observed during muscle loading (Annex 2).

3.1.5. Comparison of articular compartments for each load (only compartments with statistically significant variation of pressures: LA/HR and LP)

A flow of articular pressure from LP to LA and HR was observed (Fig. 3). A statistically significant increase in pressure in HR (0, 1, and 5 kg) and LA (3 and 5 kg) corresponded with a decrease in the LP joint pressure.

4. Discussion

In our study, we found that HR pressure increased in both groups. In the epicondylar group, the increase was statistically significant for all loads. In the epitrochlear group, although we expected progressive loading of the tendons to generate distractive HR forces, we observed a statistically significant pressure increase for loads under 3 kg. This behavior could be explained by an initial effect of proximal translation of the forearm with lower loads and a progressive growing varus moment with higher loads when the anterior trochlea acted as a pivot point.

Until now, biomechanical studies of the contact areas and the distribution of pressure in the elbow have generally focused on the alteration of physiological conditions of the joint (Anand et al., 2015; Chantelot et al., 2008; Eckstein et al., 1994; Eckstein et al., 1993; Morrey et al., 1988; Ofuchi et al., 2001; Van Riet et al., 2004; Willing et al., 2013); that is, they have focused on the insertion of the sensors into the joint (Dos Remedios et al., 2003) or have used specimens receiving previous formalin fixation (Chantelot et al., 2008; Eckstein et al., 1994; Eckstein et al., 1993; Goel et al., 1982) which modifies physiological properties of the tissues. Therefore, our study maximized tissue hysteresis since we used fresh cadaveric specimens that were not previously manipulated and only performed an anterior and posterior capsulotomy to insert the sensor into the compartment. Other biomechanical studies evaluating elbow stability developed valgus/varus gravity models (Ahmed and Burke, 1983; Anand et al., 2015; Golan et al., 2016; Hassan et al., 2015; Park and Ahmad, 2004; Pomianowsky et al., 2001) not useful for our purpose of representing physiological conditions. Therefore, unlike previous studies, we attempted to generate forces in an intrinsic way and with the elbow at 90° flexion, because the elbow remains in flexion during much of our daily activities (Yu et al., 2018).

Under physiological loading, muscle contraction causes axial forces and varus and valgus stresses (Morrey et al., 1991) and, more specifically, muscles with the same anatomical origin cause similar changes in pressure compartments when loading their respective tendons. A common pressure distribution pattern has been identified for epitrochlear and epicondylar groups (Table 1). Interaction of varus and valgus forces possibly led to posterior displacement of the forearm post. We believe conducting the traction cords through the bone tunnels helped to more accurately preserve the direction of force vectors generated by tendon loading.

Some authors have utilized traction cords for loading muscles from 1 to 5 kg (Morrey et al., 1988; Ofuchi et al., 2001; Park and Ahmad, 2004; Pomianowsky et al., 2001; Van Riet et al., 2004) We did not consider individual muscle force potential in regard to cross sectional area because our objective was to observe a relationship between muscle loading and pressure distribution. Some comparisons between two compartments for a specific load did not show statistical significance. This is remarkable because some of the pressures were inversely related; that is, in one compartment there was a progressive increase in the pressures following an increase in muscle loading, while a decrease in pressures occurred in another compartment. The crossing point of these values (where they were closest) was not found to be significant (Fig. 3).

On the other hand, several previous studies have demonstrated that joint contact areas and articular pressure change with pronosupination (Diab et al., 2005; Morrey et al., 1988; Ofuchi et al., 2001). In that sense, our mechanism for pronosupination blocking did not affect force transmission through the interosseous membrane.

Many previous studies have focused on the radiocapitellar joint or trochlear notch, but none have considered all six articular compartments of the elbow (Chantelot et al., 2008; Diab et al., 2005; Eckstein et al., 1994; Morrey et al., 1988; Ofuchi et al., 2001; Van Riet et al., 2004). We analyzed the compartments individually because introducing more than one sensor simultaneously could significantly modify the pressure readings.

Direct methods, such as pressure sensors, allow more reproducible and accurate results than indirect methods (Kocaoğlu et al., 2015; Sellei et al., 2013). Bachus et al. found TekScan systems to be more accurate than the Fuji Film methods for estimating area and pressure (Bachus et al., 2006). Other advantages of these systems include a smaller profile and the ability to produce real time data and evaluate a wider range of loads. Furthermore, Fergusson-Pell demonstrated that Flexiforce sensors have acceptable drift, repeatability, and linearity (Ferguson et al., 2000).

We did not test loading effects on the distal biceps tendon because of its tendency to dislocate the HR joint at 90° flexion, as demonstrated by Morrey et al. (1988). That study also indicated that the brachialis muscle only affects the HR joint indirectly (Morrey et al., 1988); therefore, its traction was kept consistent during all testing sessions for each specimen.

We could not successfully reproduce the muscular function of the supinator because its insertion could not be stapled.

4.1. Limitations

Future studies should observe how articular pressure changes under in vivo conditions, when many muscles are being utilized simultaneously.

5. Conclusions

Our study found that the humeroulnar joints are under higher pressure stresses than the humeroradial joint when loading each tendon individually.

The joint pressure distributions were dependent on which muscle group was loaded. These patterns were related to the valgus or varus moment that the epitrochlear or epicondylar muscles generated at the joints; therefore, every muscle has a specific influence on articular pressure distribution.

Significant pressure changes did not occur in the MP compartment when the epicondylar muscles were loaded or in the LP compartment when the epitrochlear muscles were loaded. The supposed increase in pressure in those compartments from varus and valgus stresses may be compensated for by a decrease in pressure influenced by the posterior translation of the ulna during muscle loading.

The anterior compartments mainly supported the increase in pressure generated by muscle traction and valgus and varus stress; this was especially true for the LA, the compartment that had the highest observed pressures.

The findings of our study can be applied to advancing physiotherapy by developing treatments that generate specific pressure patterns within the joint compartments. Decreasing pressure in those that have sustained injury while reinforcing others.

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Declaration of Competing Interest

The authors, their immediate family and any research foundation with which they are affiliated did not receive any financial payment or other benefits from any commercial entity related to the subject of this article.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.109378.

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