Elbow Joint Dislocation

An experimental evaluation of the pathokinematics

Ph.D. thesis

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Contents

Preface

This thesis is based on research conducted at the Orthopaedic Research Laboratory, Aarhus University Hospital, Denmark, from August 1999 to June 2002. I was employed as a clinical assistant to Professor Otto Sneppen, M.D., D.M.Sc., Department of Orthopaedics, Aarhus University Hospital, from November 1999 to January 2002. In the remaining periods I worked as a registrar at the Department of Orthopaedics E, Århus University Hospital.

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My children Frederik, 5, Nikolaj, 5, and Louise, 1 (Louise during the last part only) often made me forget research for a while, pauses which proved both necessary and stimulating.

Dec 2002

Abbreviations

AL	annular ligament
AMCL	anterior medial collateral ligament
CP	coronoid process
LCL	lateral collateral ligament
LCLC	lateral collateral ligament complex (AL+LCL+LUCL)
LUCL	lateral ulnar collateral ligament (posterior fibres of the LCL)
MCL	medial collateral ligament (AMCL+PMCL)
PEFR	pathological external forearm rotation
PLRI	posterolateral rotatory instability
PMCL	posterior medial collateral ligament
PST	posterolateral stress test
RH	radial head

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Wright Medical Technology Inc., Arlington, TN, granted the Evolve® prostheses for the third study.

Manuscripts

1. Deutch SR, Jensen SL, Olsen BS, Sneppen O: Elbow Joint Stability In Relation To Forced External Rotation. Accepted for publication. Journ. Shoulder Elbow Surg.
2. Deutch SR, Olsen BS, Jensen SL, Tyrdal S, Sneppen O: Ligamentous and Capsular Restraints To Experimental Posterior Elbow Joint Dislocation. Submitted. Scand. Journ. Med. Sci in Sports 2002
3. Deutch SR, Olsen BS, Jensen SL, Tyrdal S, Sneppen O: Elbow Joint Stability following Experimental Osteoligamentous Injury and Reconstruction. Accepted for publication. Journ. Shoulder Elbow Surg.

Background

"*Instability and fractures following dislocations of the elbow joint are significant injuries that can result in permanent dysfunction of the elbow with considerable impairment in daily life.*"

Morrey

Epidemiology

Elbow joint dislocation has an annual incidence of 6 per 100.000, the median age being 30, but the mode in the late teens in both men and women.[30] Almost all dislocations are posterior.[34] The two main complications of simple dislocations are contractures and recurrent instability,[28,45] and up to 60 % of patients suffer long-term complications.[4,28,37] Posttraumatic ligamentous insufficiency leads to instability; some authors report a prevalence of 15%.[28]. Recurrent dislocations are very rare after simple dislocations, but occur in a few percent after fracture-dislocations.[27,43,57] Concomitant fractures occur in 10-15 % of dislocations.[4,5,14,27,33,34,43,54,57] Associated injuries are present in 25-50% of cases; i.e. osteoligamentous injuries in other joints[28] or vascular and neurological injuries near the elbow.[29]

Dislocation mechanism

As a high-energy trauma will have a destructive impact on the elbow joint, any mechanism of ulno-humeral dislocation is possible and this may result in a fracture-dislocation. However, the typical reason for dislocation is a low-energy trauma from a fall on the outstretched hand.[57] This most often results in a simple dislocation without adjacent fractures, though specific and reproducible pathokinematics of this type of dislocation has not yet been established.

An axial compression force of the elbow joint resulting from a fall on the outstretched hand is the obvious primary mechanism of the simple posterior dislocation. Osborne and Cotterill (1966) were the first to suggest an external forearm rotation as a necessary initial step of the simple posterior elbow dislocation.[51] This theory was not based on experimentation, but on clinical investigation of 18 cases of recurrent elbow joint dislocation. The authors state that the "posterolateral rotation movement" of the forearm is a result of an axial force compressing the coronoid process on to the laterally sloping surface of the trochlea. Clinically, they found the lateral collateral ligament complex more lax than on the medial side. This was correlated to the fact that a posterolateral rotation movement would make the radial head (RH) dislocate over a larger distance when rotating through a greater arch than the ulna. [51]

Sojbjerg *et al* (1989) introduced valgus force as a factor in elbow dislocation, and reported external rotation and valgus moment at 30° to result in dislocation, but the axial force was not investigated. [62] Other authors considered valgus force as a part of the dislocation. O'Driscoll *et al*.(1992) suggested that dislocation results after an axial force at 80° of joint flexion, external rotation (34°-50°), and a valgus moment.[47] The valgus moment was one of three forces manually used to dislocate cadaver specimens in an experimental study, and the introduction of valgus force in the experiments was based on theories regarding forces impacting the elbow *in vivo* during a fall on the outstretched hand.[47] The authors also stated that the posterior dislocation was the final stage in a circle concept of elbow joint dislocation.[47] Prior to this, O'Driscoll had introduced posterolateral rotatory instability (PLRI) as a clinical entity[45], and in his 1992 study PLRI was defined as the first stage in the spectrum of instability leading to posterior dislocation, i.e. the first stage in a pathological external forearm rotation.[47]

PLRI may be seen after a simple sprain or after posterior subluxation or dislocation, and it is the most common pattern of elbow instability.[45] The study by O'Driscoll *et al*[47] found the dislocation to occur without rupture of the medial collateral ligament (MCL), which is in contrast to perioperative observations of acute dislocations by Josefsson *et al*.[29] They found both collateral ligaments ruptured in all cases, suggesting that a complete posterior dislocation cannot occur without bilateral collateral ligament disruption. O'Driscoll *et al*.[47] introduced the "Circle Concept" for soft tissue damage during posterior dislocation which describes progressive capsuloligamentous disruption in three stages, starting laterally and continuing both anteriorly and posteriorly towards the medial side of the joint, but sparing the anterior medial collateral ligament (AMCL) from disruption.

Hence, it seems that full agreement between experimental studies and clinical observations regarding the dislocation mechanism remains to be established.

Previous experimental models

Different experimental models have been used in studies of posterior elbow dislocation. Sojbjerg *et al*[62] fixed the humerus and manually applied increasing valgus and external rotatory force to the forearm at a joint flexion of 30 degrees until dislocation, an axial force being not considered.[62] The model used by O'Driscoll *et al* introduced an electro-magnetic tracking system in order to detect extension-flexion, valgus-varus, and rotatory movements of the forearm during kinematic experiments.[2,47] In the same time, it applied dynamic joint compression forces by attachment of weights to different muscles. The flexion-extension and the rotatory forces were applied manually and were not quantified, but the system yielded a precise description of kinematic (flexion, rotatory, and valgus-varus) changes in the joint. In contrast to Sojbjerg *et al*'s study[62] that was performed with intact ligaments, O'Driscoll *et al*[47] incised all ligaments but the AMCL previous to the dislocation mechanism, which was performed manually. Both studies did not quantify the rotatory nor valgus forces needed to dislocate the joint with regard to magnitude or direction.

A recent study by Johnson et al[26] compared the reproducibility of the joint kinematics in passive and active testing of the intact elbow joint using a compression-movement-controlled model. The model was equipped with an electro-magnetic tracking system similar to the one used by O'Driscoll *et al*.[47] Pneumatic actuators generated the joint compression and joint movement through attachments to muscles, and the authors concluded that active control of movement compared to passive (or manual) movement of the joint increased the reproducibility of the joint kinematics measurements.

Thus, none of the previous studies have applied pathokinematic movements or forces to the joint in order to induce a reproducible posterior dislocation.

The osseous constraint

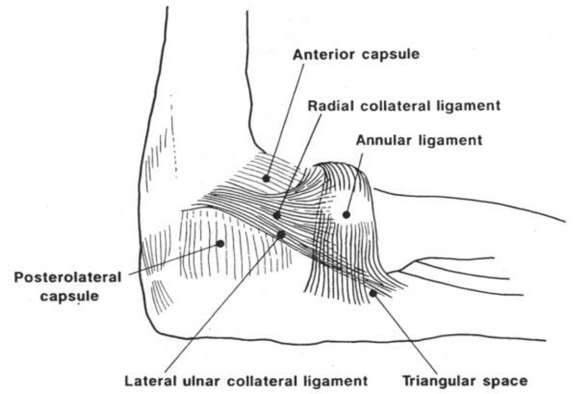
In the intact elbow joint the deep trochlear notch of the ulna surrounds almost 180 degrees of the humeral trochlea, making the elbow one of the most confined articulations in humans and accounting to a large extent for its inherent stability throughout the flexion arch. The interdigitation of the central groove in the trochlea with a corresponding ridge in the trochlear notch adds stability to the articulation.[61]

Studies concerned with the overall stability of the elbow joint discuss the inherent osseous stability, but the osseous constraint to forearm rotation has not been quantified experimentally.[3,22,38,41,54] Forearm rotation is considered to be a part of the dislocation mechanism (simple dislocation) and to be the biomechanical phenomenon of PLRI as mentioned earlier.[45] Axial force from the forearm, as from a fall on the outstretched hand, is transmitted equally through the radius and ulna.[16] Valgus force is a part of the most recent theory regarding biomechanics of the posterior dislocation[47], and is furthermore a part of the clinical test for PLRI.[45]

Previous studies state that elbows with isolated insufficient collateral ligaments are most resistant to lateral rotational instability in the pronated position.[7,10,45,47,49] Whether this relates to osseous or ligamentous factors, however, has not been previously investigated.

Capsuloligamentous constraint

Lateral collateral ligament complex (LCLC).



In 1980, Schwab *et al* reported that the elbow did not posses a functional lateral ligament.[59] Since then, many authors have described and emphasized the importance of the LCLC as a stabilizing component of the joint, and some described the lateral ulnar collateral ligament (LUCL) as a separate component of the LCLC.[39] A recent study underlined the importance of this ligament after serial sectioning of lateral soft tissue structures including tendons and muscles.[7] The LCLC is generally considered as one of the structures which maintain apposition of the RH and the capitellum, and therefore are critical to the stability of the elbow.[7,20,25,49,65] More authors described recurrent elbow sprains to be the cause of PLRI.[42,45,47] Two studies stated that both the lateral collateral ligament (LCL) and LUCL have to be severed before PLRI occurs.[9,17] Other authors found LCLC rupture necessary before external rotation occurred in clinincal studies of PLRI,[38,42,45] and Josefsson *et al*.[29] observed rupture of LCLC (and the MCL) following *in vivo* dislocation in all cases in a prospective series of observations preoperatively in the acute stage. However, the LCLC has not been evaluated as a constraint to external rotation during simultaneous joint compression force. Furthermore, an increasing number of authors question the anatomical and functional significance of the LUCL.[7,23,49,50]

Medial Colateral Ligament (MCL).

The anterior bundle (AMCL) in the MCL is easily identified in anatomical dissections, whereas the posterior and transverse bundles appear as subtle capsular thickenings.[15] Attenuation of the AMCL has been associated with difficulties during large valgus loads such as throwing, but it does not cause recurrent dislocations in the absence of associated injuries.[8]

In O'Driscoll *et al*.'s[47] "Circle Concept" for posterior dislocation, which describes progressive capsuloligamentous disruption in three stages, starting laterally and continuing both anteriorly and posteriorly towards the medial side of the joint, the authors state that the AMCL is not necessarily disrupted in a posterior dislocation of the elbow. This statement was based on an experimental study[47], but it contradicts the findings of Josefsson *et al*[29] who found all ligaments to be disrupted after a posterior dislocation in a clinical study of acute posterior dislocation.

Morrey *et al*[41] originally introduced the terms "primary and secondary" constraints. A primary constraint is mandatory for stability in relation to a certain force; hence full stability is lost in the absence of a primary constraint. Isolated removal of a secondary constraint does not alter stability, a secondary constraint only having stability influence in cases of primary constraint deficiency.

The MCL has been characterised as the primary constraint to valgus stress in an earlier study[41], and other authors found both internal rotation and valgus laxity in a kinematic study.[65] With an absent RH, MCL insuffiency leads to gross valgus instability.[41]

As fibers from the AMCL are attached to the base of the coronoid process (CP), large fractures of the CP might compromise the stabilising role of the AMCL. The role of MCL as a constraint to external forearm rotation has been investigated in a kinematic set-up in our laboratory,[12,13,62] MCL insufficiency being found to increase valgus and internal rotatory laxity.

An evaluation of the MCL as a constraint to external rotation during joint compression or in association with fractures has not been performed.

Joint capsule.

As the joint capsule is the only capsuloligamentous structure anteriorly in the joint, it might have an independent role as constraint to forearm rotation. In a study with sequential severance of osteoligamentous structures the anterior capsule was suggested to have up to 40% of the elbow's resistance to valgus stress, and one-third of the resistance to varus stress when the elbow is in full extension.[38] With the collateral ligaments intact, a kinematic study incised the capsule and found no changes in joint laxity to valgus-varus and rotatory stress.[44] The capsule has not been previously evaluated as a constraint to rotational forces during joint compression.

Osteoligamentous lesions

Limited data address combined osteoligamentous damage in the elbow joint in the literature. Instability following these complex injuries is focused on in clinical studies,[5,11,18,27,33,43,56,58,68] whereas most experimental studies describe the laxity following ligamentous[3,7,12,15,17,22,23,38,39,44,47-50,52,55,62,64,65,67] or osseous injuries.[1,25,31,32,46,54]

Two experimental studies investigated combined osteoligamentous injuries.[41,63] Sojbjerg *et al*[63] examined the valgus-varus and internal-external rotation laxity after stepwise transection of the annular ligament (AL), RH, and LCL. They concluded that the AL was the prime stabilizer of the lateral aspect of the elbow and that the LCL had only a minor stabilizing function on the elbow. Morrey *et al*[41] defined the MCL as the primary constraint to valgus stress and the RH as the secondary constraint and, in contrast to most other studies, that absence of the RH did not alter the motion characteristics of the elbow.

The structures most frequently fractured in relation to posterior dislocation of the elbow in adults are the RH and the CP, and in children they are the RH and the condyles.[4,5,14,27,33,34,43,54,57] This is partly substantiated in an experimental study where a destructive force was impacted along the forearm axis in order to create fractures similar to the *in vivo* situation.[1] RH and CP fractures followed impact along the forearm with up to 80 degrees of flexion, whereas distal humeral fractures occurred at flexion above 110 degrees.[1]

Closkey *et al*[6] recently investigated consequences regarding axial shortening of the arm following experimental CP fractures in cadaver specimens. They concluded that a fracture involving up to 50% of the coronoid height had no influence on the axial stability. Rotational stability following CP fracture has not been previously investigated.

The RH contributes to stability in several ways. In an otherwise intact joint, RH excision has been shown to decrease stability to forced varus and to external rotation.[25,63] In joints with insufficient MCL, another study showed increased laxity in the valgus stressed elbow following RH excison, this laxity decreasing after RH prostheses implantation.[31] Clinically, RH excision may induce proximal radial migration. This may be prevented with RH prosthesis.[32] From the clinic it is known that up to 92% of cases suffer from arthrosis ten years after RH excision without replacement.[5]

The combination of posterior elbow dislocation with fracture of both the CP and the RH is referred as the "Terrible Triad", originally suggested by Hotchkiss.[21] Such a situation needs surgical restoration *in vivo*, but experimental studies comparing stability of the elbow after different surgical procedures has not been made.

Hypotheses and aims

Hypotheses:

I. The elbow joint is most susceptible to posterior dislocation induced by external forearm rotation and axial compression force at a certain joint position.

II. The LCLC is the primary constraint in relation to external forearm rotation, and subsequently to posterior dislocation of the joint.

III. The RH, the CP, the MCL, and the capsule are secondary constraints to external forearm rotation and ultimately to posterior dislocation.

IV. In the case of the "Terrible Triad", a reconstruction of the LCLC is the most important procedure in order to reestablish rotatory stability to external forearm rotation.

Aims:

1. Development of a Joint Analysis System suitable for reproducible testing of human cadaver elbow joint specimens in relation to the hypothesized mechanisms and joint constraints of posterior dislocation.
2. Determination of the inherent osseous elbow constraint to forced external forearm rotation in different flexion positions, different valgus/varus stresses, and during different supination/pronation positions. This specifies the position of the elbow joint with the least osseous constraint to dislocation.
3. Determination of primary and secondary constraints to external rotation and dislocation among the following structures: LCLC, MCL, joint capsule, RH, and CP.
4. Evaluation of stability to forced external forearm rotation and dislocation in joints with the "Terrible Triad" following selected clinical reconstructive procedures.

Material and methods

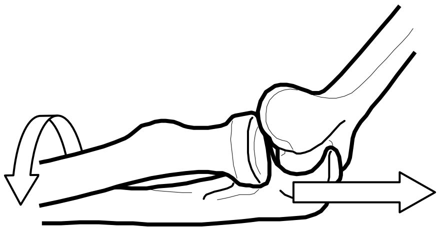
Specimens

Thirty-nine cadaveric elbow specimens were considered in the three experimental series (6+18+12(+3 excluded)), and eight were used for pilot studies. In the experimental group, 19 were right and 20 were left autopsy specimens from 30 individual donors, all cut at the mid-humeral and carpo-metacarpal level. Sixteen donors were women and 14 men, and the mean age was 72 years (range 59-88). All specimens were obtained within 48 hours postmortem and kept frozen until inclusion. Three specimens with signs of prior fractures or advanced osteoarthritis were excluded. Except in the first series where all soft tissues at the elbow joint were removed, a careful dissection was initially performed preserving the joint capsule with ligaments, the interosseous membrane and the radio-ulnar articulations.

Experimental set-up

As indicated in the hypotheses section, we presupposed that an external rotation, together with an axial compressive force, were conditions for the simple dislocation to occur. This is illustrated in Fig. 1 as pathological external forearm rotation (PEFR).

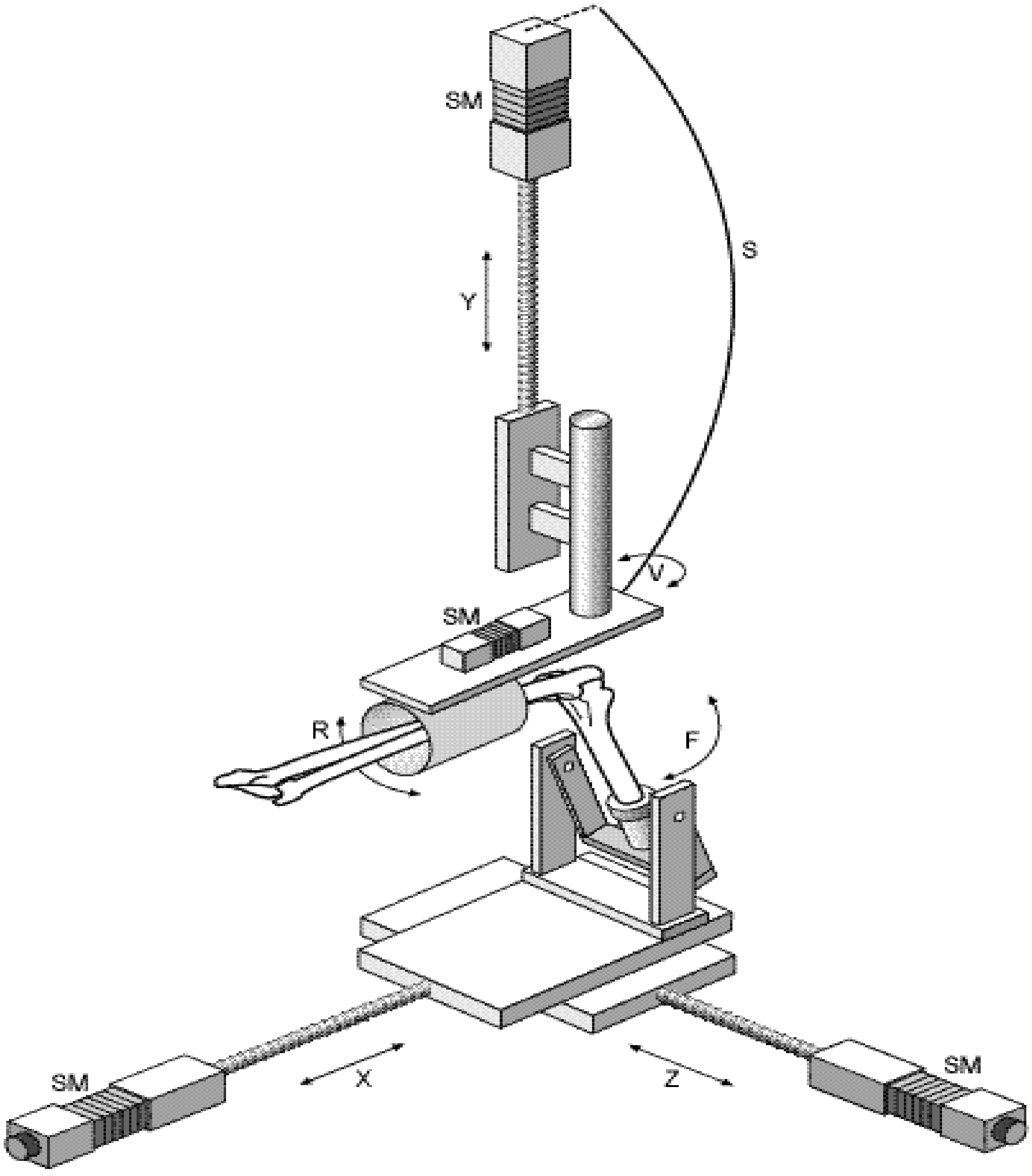
To simulate the posterior elbow dislocation under simultaneous control of joint compression forces and pathological movements in the joint, we developed the Joint Analysis System (JAS), as illustrated in Fig. 2.



<u>*Figure 1*</u>

The Pathological External Forearm Rotation (PEFR) (curved arrow) combined with the axially directed forearm force (straight arrow).

The JAS works in the three dimensions of a coordinate system (X, Y and Z), with rotation (R) possible about the X-axis (Fig. 2). The humerus is mounted on a platform which permits horizontal movement in any direction in the X-Z plane. The elbow flexion (F) is fixed in each test, and it is preset and changed prior to each test by tilting the humeral fixator about the Z-axis. Flexion is possible from approximately 110 degrees to the fully extended position. The cylindrical fixation device for the forearm is mounted horizontally on a vertical pillar that provides vertical movement for the horizontally positioned forearm along the Y-axis (Y). In the cylinder, the forearm can be rotated about the X-axis. The forearm fixation device is constructed to allow free movement in the horizontal plane about a vertical axis perpendicular to the forearm and centered through the deepest point of the ulnar joint surface. The JAS thus allows the forearm to swing unconstrained horizontally during a test (V in Fig. 2). Furthermore, we are able to apply a constant varus or valgus torque to the joint by pre-test winding of a steel wire (S in Fig. 2).



<u>*Figure 2*</u>

The Joint Analysis System (JAS) with a specimen mounted. The axes of linear movement are marked X, Y and Z, and PEFR rotation about the forearm is marked R. These movements are controlled by stepping motors (SM). F denotes elbow flexion, which is preset, and V is the free horizontal (valgus-varus) movement. The steel wire for applying valgus-varus stress is marked S.

The JAS is controlled by a personal computer equipped with the LabVIEW® software (National Instruments®, Austin, Texas). The computer controls switch units (Berger-Lahr®, Germany) for four step motors (SM) (Berger-Lahr®, Germany), each providing the movement along one of the linear axes or the rotation about the X-axis. The JAS permits movement in steps of 5 μm in the XYZ-coordinate system and in steps of 0.037° of forearm rotation, and works with a maximal speed of approximately 80 steps per second. To collect data regarding the forces impacting the joint, one pair of strain gauges is mounted on the fixation unit corresponding with each axis and rotation. By four amplifiers custom made at our laboratory, the computer collects real-time data of the force from all four sets of strain gauges after each step of movement, and movement data from the four step motors. Data are saved in a log file. The JAS allows force measurement with a precision of 0.01 N in the three linear axes and in rotation. It is calibrated with weights prior to specimen mounting.

The experimental sep-up remained unchanged during the experiments, except that the steel spring was not used in Studies 2 and 3 where valgus-varus force was not considered.

Experimental protocols

Study 1. Six elbow joint specimens with intact bone and cartilage (three left and three right) from six males with a median age of 79 years (range 75-84) were included. To mark the elbow flexion axis, a Kirschner wire was drilled through the trochlea in the axis of elbow flexion. This axis lies through the centers of the arcs formed by the trochlear sulcus and the capitellum[36]. Before mounting the forearm in the JAS, the fixed supination-pronation position was secured with a 3.5 mm cancellous screw at the radial neck level transfixing the ulna and radius in the chosen position. The forearm was then positioned in the centre of the cylinder (Fig. 2) and secured with screws applied against the bones from multiple directions. When the supination-pronation position was changed between the tests, the forearm was dismounted from the cylinder and the cancellous screw repositioned. The axis of the PEFR was chosen as a line from the center of the proximal radioulnar joint to the center of distal ulna, because axial force from the forearm is transmitted to the humerus almost equally through the radius and ulna[16]. This axis was centered in the cylinder, thereby being the forearm PEFR axis when the cylinder was mounted in the JAS. The humerus was fixed in the JAS as shown in Fig. 2. As our aim was to elucidate the general osseous constraint of the elbow joint to PEFR, also during immobilisation, we decided to test our specimens not only in supinated position but also in neutral and pronated positions.

Variable factors were joint flexion (0, 10, 20, 30, 45 and 90°), forearm supination-pronation position (maximal supination, neutral, maximal pronation), and valgus-varus torque ($2.25 \ast 10^{-3}$ Nm). Hence, each specimen was tested in 54 different combinations of the variable factors.

The torque (Nm) applied to the forearm was calculated as the measured rotational force (N) times the cylinder radius (4.4 cm). The maximal torque value was defined as the highest moving average of 10 measurements. The total work needed to reach the point of maximal torque was calculated as the angle of rotation (radians) times cylinder radius (m) times the average force measured (N) in ten step intervals. Each test was manually terminated when the ulnar angular movement resulted in coronoid process dislocation posteriorly in the trochlear groove.

Study 2. Eighteen fresh frozen upper extremities (four left and 14 right) obtained from 12 females and 6 males with a median age of 77 years (range 65-93) were used. All soft tissues except the capsule with ligaments and the interosseous membrane were removed. The specimens were tested only in the fully supinated position. This was considered relevant as it seemed unlikely that the pronator muscles *in vivo* are strong enough to prevent a complete supination in the forearm previous to a PEFR when an external rotatory torque impacts. Joint stability was defined as the PEFR possible until an external rotatory torque of 1.75 Nm was reached. This torque was sufficiently low as not to damage the soft tissue constraints yet high enough to demonstrate laxity. In a pilot study using two specimens, five repeated measurements until the torque limit of 1.75 Nm showed no increase in PEFR angle due to lesions of the capsule during the previous tests.

The specimens were tested in different flexion angles to evaluate a possible difference in ligamentous function. Variable factors were joint flexion (0, 30, 45 and 90°) and the six cutting sequences of ligaments and capsule, with three specimens in each, as shown in Fig. 3. The incisions of the LCLC were divided into an anterior part anterior to the longitudinal radial axis, and a posterior part posterior to the axis (Fig. 3).

1	Ant cap	Post cap	pLCLC	aLCLC	MCLC
2	Post cap	Ant cap	pLCLC	aLCLC	MCLC
3	Ant cap	Post cap	MCLC	pLCLC	aLCLC
4	Post cap	Ant cap	MCLC	aLCLC	pLCLC
5	aLCLC	pLCLC	Ant cap	Post cap	
6	pLCLC	aLCLC	Post cap	Ant cap	

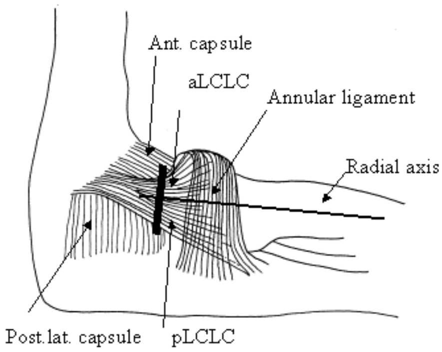


Figure 3

The six test sequences in Study 2 (1-6 in the table) with 3 specimens in each group, and illustration of lateral ligament section (line). Anterior LCLC (aLCLC) + posterior LCLC (pLCLC) = lateral collateral ligament complex = (LCLC), and MCLC is medial collateral ligament complex (not shown).

Study 3. Twelve elbow joint specimens (nine left and 3 right) obtained from 9 females and 3 males with a median age of 75 years (range 65-89) were included. Soft tissues including the joint capsule were removed, leaving the interosseous membrane and the ligaments intact (LCLC+MCL). The specimens were divided in four groups with different sequences of standard fractures, ligament injuries, ligament reconstruction, and RH prosthetic replacement (Table 1).

1	Intact	RH-exc	LCL-recon	MCL-inc		
2	Inatct	CF st2	RH-exc	MCL-inc		
3	Intact	CF st2	RH-exc	RH-prost	MCL-inc	LCL-recon
4	Intact	RH-exxc	CF st2	RH-prost	MCL-inc	LCL-recon

Table 1
The four test sequences in Study 3. Initially, the intact joints were tested. Next, the joints were tested after fractures with or without adjacent severance/reconstruction of ligamentous structures. (CF st2 = coronoid fracture stage 2)

The RH was excised without disrupting the annular ligament by retracting the anterior part of the annular ligament distally. A modular RH prosthesis was used (Evolve®, Wright Medical Technology Inc., Arlington, TN) in order to match as closely as possible the diameter and height of the excised RH. Both the height and diameter of the radial head were measured after excision and matched carefully by selecting from the large variety of prostheses available. In order to spare the soft tissue constraints, the prosthesis was implanted after an osteotomy of the lateral epicondyle, and the osteotomy was later refixated in the anatomical position with cancellous screws, as depicted in Fig. 4.

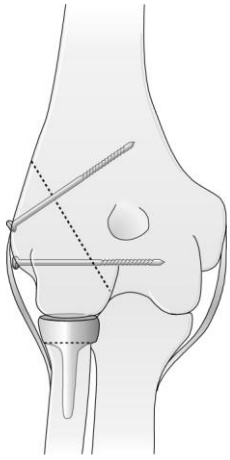


Figure 4
The osteotomy of the lateral condyle refixated with screws after prosthetic replacement of the radial head.

The coronoid fracture was a Stage II according to the Regan and Morrey classification,[54] in which the height of the coronoid is reduced by 50%. In a pilot study involving 3 specimens a CP stage 1 fracture (tip of CP) was investigated, and this situation did not differ from the intact state in our set-up.

The lateral collateral ligament was reconstructed according to the method described by Morrey *et al*[40] with a 10 mm (width) mid-triceps graft. With the joint in 90 degrees of flexion, boreholes and heavy sutures in the supinator crest and in the isometric point of the lateral epicondyle fixed the graft after a tension of 5 Newton was applied.[40] We knew from Study 2 that gross laxity would occur without the reconstruction of the LCL, so this situation was not tested. From the same study we also knew that the MCL is not a restraint to PEFR in joints without fracture, but that might change after a fracture. Therefore, MCL incision after fractures was a part of Study 3.

Throughout the three studies, constant factors during all tests were a forearm axial force of 15 N (along the X axis), and a joint compression force of 5 N perpendicular to the forearm thereby acting vertically downwards (along the Y axis). Both forces were relatively minor to avoid damage on the articular surfaces during the tests. The Z force was automatically kept within 0± 0.25 N during all tests.

The maximal joint congruence in each position was defined as the start position. This was reached by manually moving the joint along the X- and Z-axes and in rotation until the deepest joint position on the Y- and X-axes were measured. During each test, the JAS applied the constant forces to the joint as the first step. It then performed the PEFR in a stepwise manner (0.037°/step), and for each step collected simultaneous data of both position and force from the three axes and from the rotation. The articular surfaces were kept permanently moist with physiological saline solution.

Statistics

In the first study the objective was to quantify the influence of different independent factors relative to the osseous constraint of the joint in relation to PEFR. Therefore, statistical analysis was performed using a variance component model as described in the Proc Mixed procedure[35] with SAS™ (SAS Institute Inc., Cary, NC, USA) statistical software. The total variance of data was divided into variances of the changing factors in the tests (stress, supination-pronation position, flexion angle, and specimen number). All factors and all effects of random interactions, for example stress×flexion, were tested for significant influence. All non-significant interactions were neglected in subsequent analyses. Lastly, the magnitude of factor influence on maximum torque, rotational work and rotation were calculated.

The second and third studies differed from the first study with respect to the number of changing factors throughout the experiments. In these two studies the objective of investigation was to evaluate the change in PEFR after different applied lesions to the specimens and after reconstructive procedures following lesion. As the results were to be compared with the intact joint, all results after lesions or repairs could be tested in comparison with the intact state of the joint. Therefore, the paired t-test was used after the results passed the test of normality (Q-Q plots in SPSS), as all data from studies two and three did. P-values less than 0.05 were considered significant.

Results

The Joint Analysis System

As a validation of the torque measurement, five repeated tests on two specimens not previously examined gave means with a standard error of 1.3% and 1.4%, respectively (range 1.0-1.6%). A similar test of the PEFR in three uninjured specimens up to a torque of 1.75 Nm gave a standard error of 1.5% (range 1.3-1.8%). Statistics based on the variance component model indicated significant differences of results obtained before and after repositioning of the forearm. Concurringly, during testing it proved difficult to re-establish a perfect centralisation of the forearm in the fixator after change of supination-pronation position.

The osseous constraint

During the pilot studies we established that the constraint to PEFR increased with increasing axial force. A typical curve of the torque needed to perform the PEFR is illustrated in Fig. 5.

The maximal torque was reached after approximately 5 degrees of rotation. At this point, the radial head was translated some distance on the capitellum, but could be observed to be quite far from dislocation. After this point of maximal torque, the curve fell in a steady manner (the area from 5 to 18 degrees in Figure 5) until complete ulnohumeral dislocation occurred.

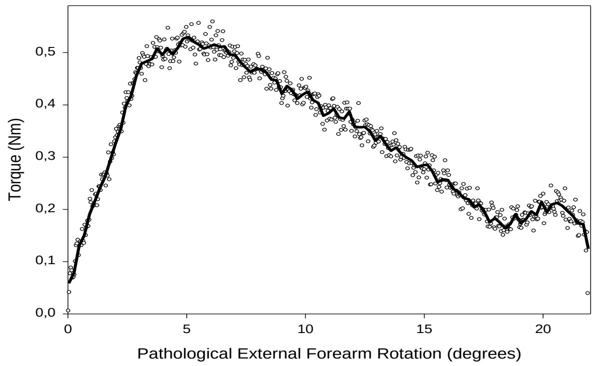


Figure 5

A typical curve of PEFR angular displacement versus the rotatory torque. The X-axis is rotation in degrees, Y-axis is the torque in Nm.

This point of maximal torque was therefore selected as one measure for the osseous constraint. The second measure was the total work needed to reach the point of maximal torque. The third measure was the rotational angle reached at the point of maximal torque. Figs 6, 7 and 8 illustrate the influence of flexion angle, supination-pronation position, and valgus-varus force on these three measures of constraint.

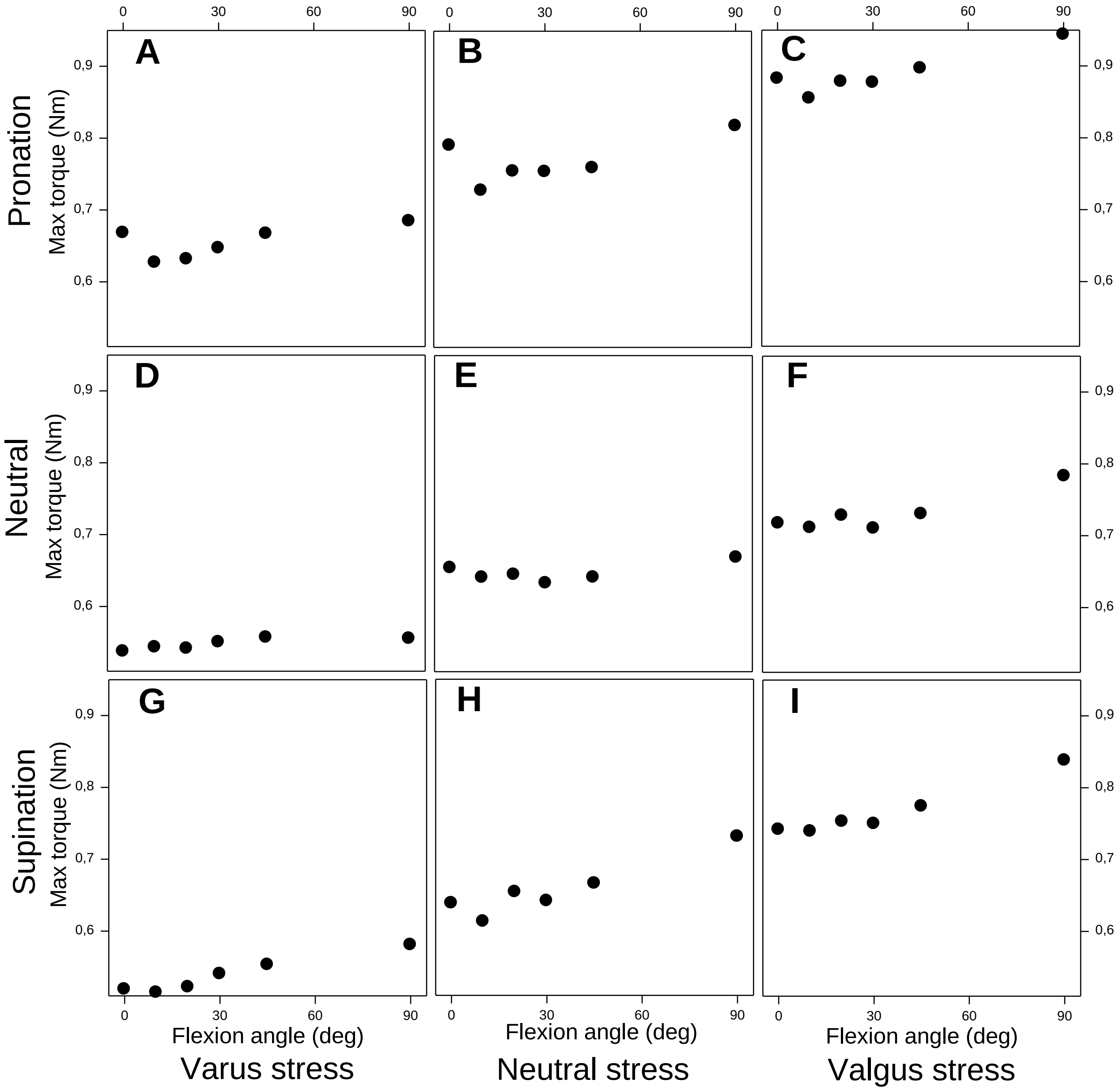
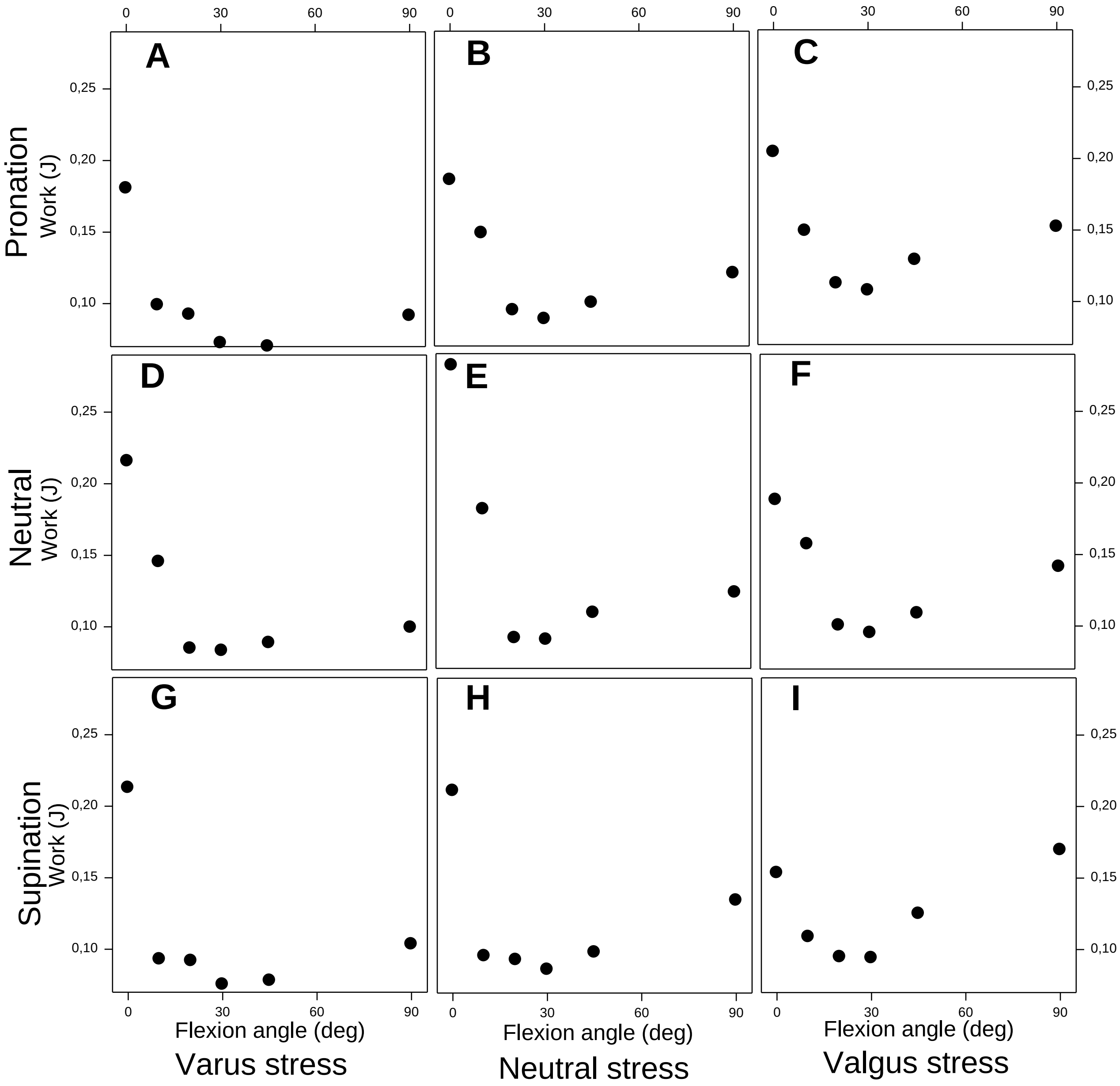


Figure 6

Mean maximal PEFR torque versus flexion angle, shown for type of joint stress and supination-pronation position respectively. The forearm is in the pronated position in the upper row (ABC), neutral in the middle row (DEF), and in supination in the lower row (GHI). Varus stress is applied to the elbow in the left column (ADG), neutral stress in the middle column (BEH), and valgus stress in the right column (CFI).



<u>Figure 7</u>

Mean forearm PEFR work until the point of maximal torque versus flexion angle, shown for type of joint stress and supination-pronation position. See legend in Fig.6 for details.

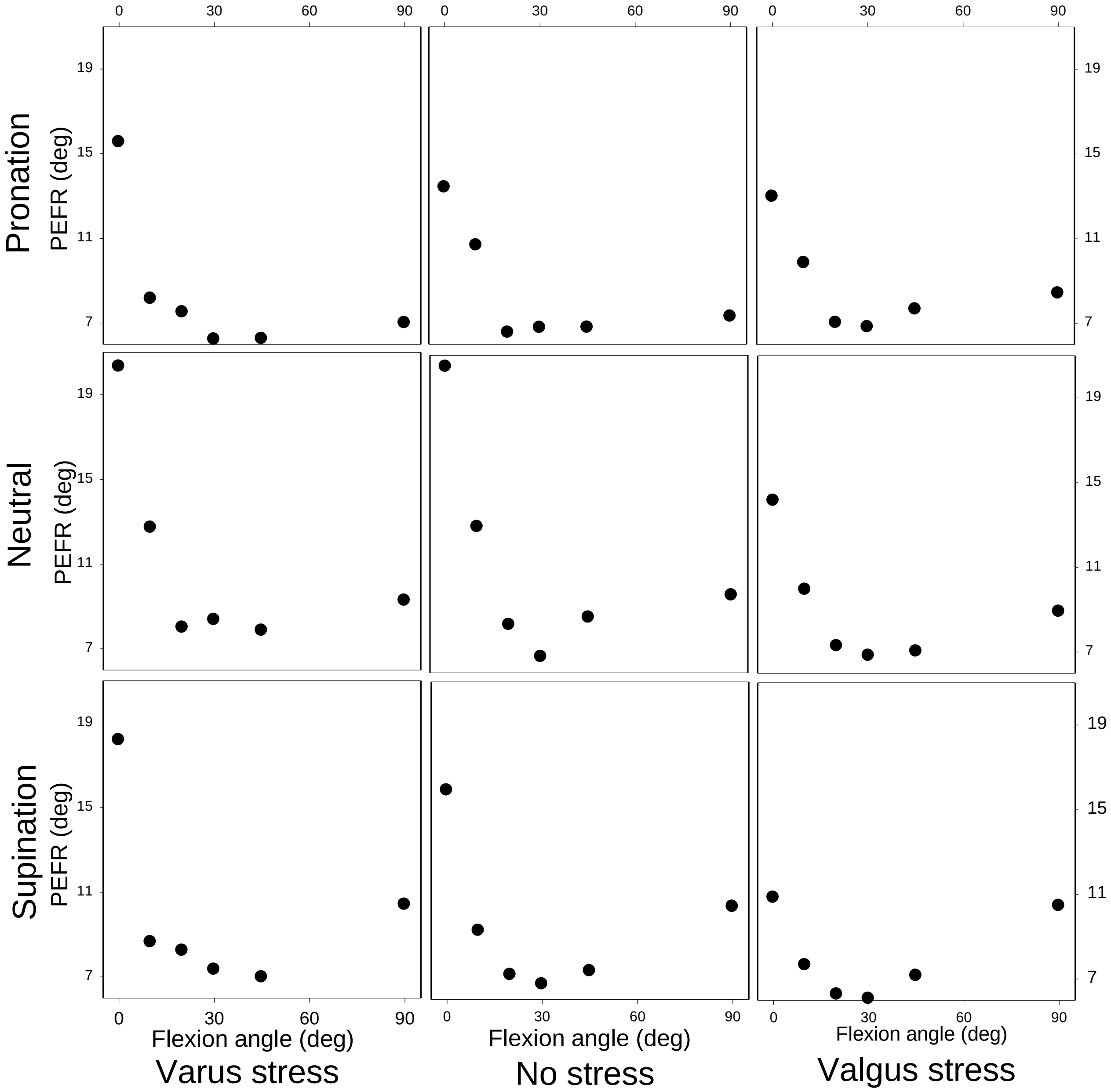


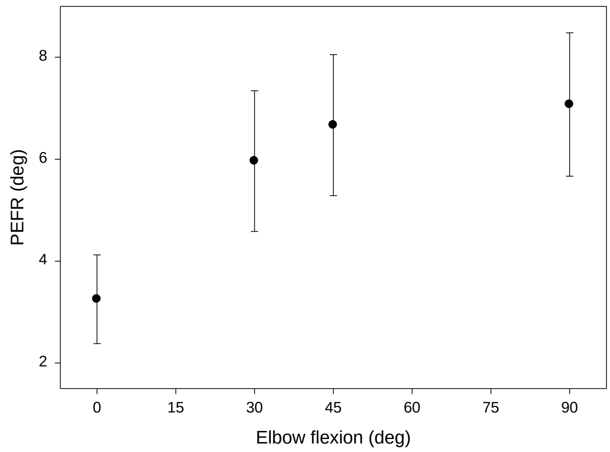
Figure 8

Mean forearm PEFR (degrees) until the point of maximal torque versus flexion angle, shown for type of joint stress and supination-pronation position. See legend in Fig. 6 for details

The torque increased from varus stress to valgus stress by 35% (p=0.0001), and it generally increased from 10° towards 90° of flexion by 17% (p=0.012). It also tended to increase from supination to pronation, but the change was non-significant (p=0.1) (Fig. 6). Thus, the osseous stability expressed as the maximal necessary torque for PEFR fell to a minimum in the slightly flexed elbow exposed to varus stress and with the forearm in supination, and reached a maximum in the 90° flexed elbow exposed to valgus stress and with the forearm in pronation. The total work of the PEFR, until the point of maximal torque was reached, decreased from a maximum in full extension to a minimum at 30° of flexion in nearly all combinations of valgus-varus stress and supination-pronation position, as shown in Fig. 7 (p=0.03). Valgus-varus stress and supination-pronation position did not influence the work (p=0.42 and 0.79) (Fig 7). The shape of PEFR until the point of maximal torque (Fig. 8) closely resembles that of Fig. 7. Hence, as found for the work, also the actual rotation decreased from a maximum in full extension to a minimum at 30° of flexion in nearly all combinations of valgus-varus stress and supination-pronation position. The similarity of these figure shapes is explained by the fact that work = distance x force. In other words, the work is closely related to the distance (which in our set-up is the rotation).

Capsuloligamentous constraint

Study 2 revealed that PEFR was possible in the intact specimens (Fig. 9); this could be defined as the inherent PEFR.



<u>*Figure 9*</u>

PEFR (degrees) until an applied torque of 1.75 Nm in the intact joint versus joint flexion angle (degrees). Mean and 95% confidence intervals are given.

Fig. 10 illustrates PEFR with the capsule or the LCLC incised relative to the intact joint (i.e. expressed as a ratio). In the extended position just a small increase of maximal PEFR is seen when only one of the structures is incised (LCLC 35%, p=0.07; capsule 48%, p=0.01), whereas in the flexed positions a larger change is seen when the LCLC is cut (i.e. at 30° 133%, p=0.04), but just a minor change is noted when only the capsule is sacrificed (10%, p=0.13). When both structures were incised, data of the maximal PEFR could not be obtained because the preset torque limit was never reached due to lack of joint constraint. In these situations the tests were manually terminated, and these results are therefore not shown.

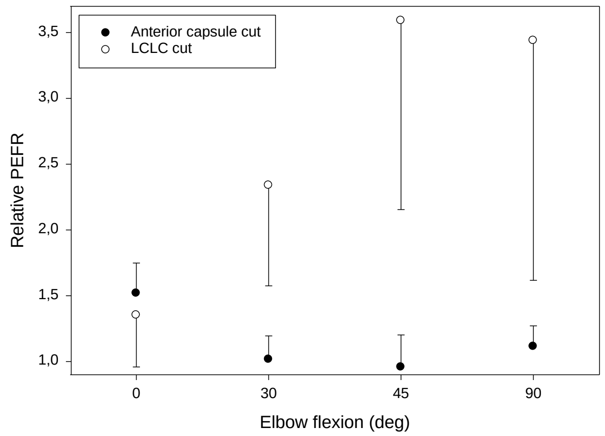


Figure 10

PEFR until a torque of 1.75 Nm after incision of the anterior joint capsule or the LCLC versus joint flexion (degrees). The PEFR is indicated as a relative measure compared with the intact joint at the same flexion angle. Mean and 95% confidence intervals are shown.

None of the 12 specimens tested with only the MCLC intact completed the posterior dislocation because in all cases the coronoid process remained anterior to the trochlea. Only with the MCLC incised did a complete posterior dislocation occur.

No difference in maximal PEFR was found after separate incision of the anterior or the posterior part of the LCLC. The entire width of this ligament complex had to be incised before any laxity occurred.

Osteoligamentous lesions

Isolated excision of the RH or the CP in Study 3 both resulted in significant PEFR increase (RH 45% and CP 28% mean respectively, both $p<0.001$), but no difference in PEFR increase between the fractures was found ($p=0.14$) (Fig. 11).

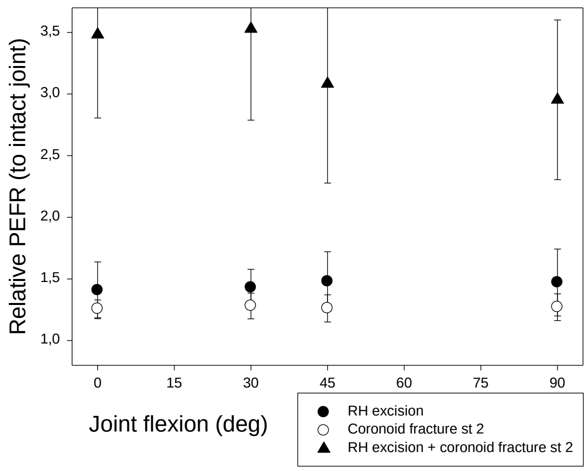


Figure 11

Relative change of PEFR (Y-axis) after RH-excision, coronoid fracture Stage II, or both in different flexion positions (X-axis). Relative PEFR as compared with the intact stage. Error bars indicate 95% confidence intervals.

After isolated Stage I CP fracture in a pilot study on two specimens we did not find increase in PEFR (1 and 3% respectively, $p=0.4$). Combined lesion of the RH and the CP (Stage II) resulted in immediate ulnohumeral subluxation after application of the axial force as the forearm migrated proximally until the radial neck met the capitellum. The PEFR increased more than 300% in this situation ($p<0.001$) (Fig. 11). Subluxation was prevented after implantation of the RH prosthesis, and except for in the extended joint position, the PEFR decreased towards the value of the intact joint (PEFR=117%, $p=0.14$) (Fig. 12). Subsequent severance of the MCL resulted in an insignificant PEFR increase (8%, $p=0.21$).

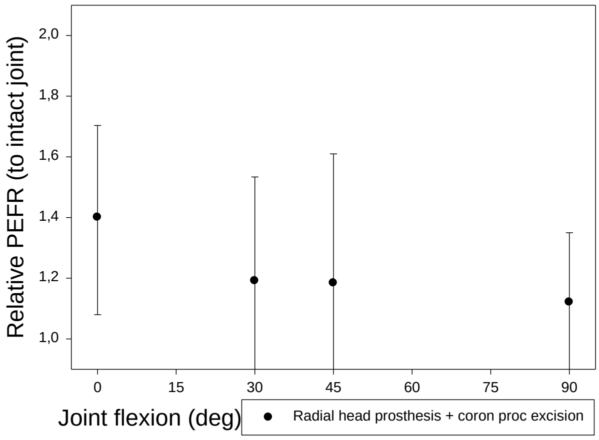


Figure 12

Relative change of PEFR (Y-axis) after RH-prosthesis and coronoid fracture stage 2 in different flexion positions (X-axis). Relative PEFR as compared with the intact stage. Error bars indicate 95% confidence intervals.

Fig. 13 illustrates differences in PEFR following RH excision, RH excision + LCL reconstruction, and the same including MCL incision. Results after LCLC severance are not shown as this removed all collateral restraint of the joint resulting in unlimited PEFR. An insignificant decrease in PEFR was seen following LCL incision and subsequent reconstruction in the joints with the RH excised (9%, p=0.18). Subsequent MCL incision in this situation resulted in an insignificant PEFR increase (7%, p=0.25).

Ultimately we tested the joint after implantation of RH prosthesis and a LCL reconstruction as a minimum operation of the "Terrible Triad" (Fig. 14). The resulting PEFR was 168% of the intact joint (p<0.001) but subluxation and gross laxity were prevented.

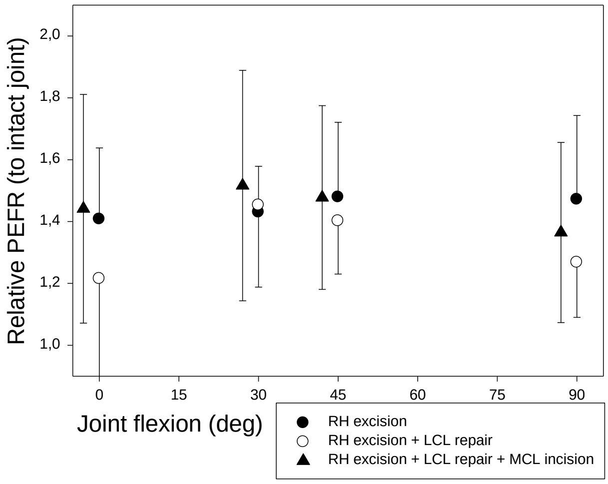


Figure 13

Relative change of PEFR (Y-axis) after RH-excision, RH-excision + LCL-reconstruction, and RH-excision + LCL-reconstruction + MCL-incision in different flexion positions (X-axis). Relative PEFR as compared with the intact stage. Error bars indicate 95% confidence intervals.

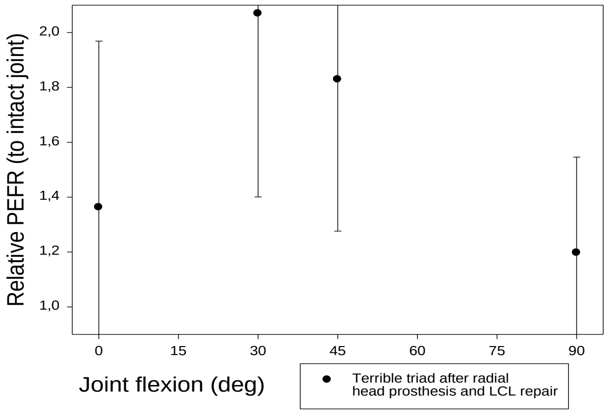


Figure 14

Relative change of PEFR (Y-axis) after RH-prosthesis and LCL-reconstruction of the"Terrible Triad" in different flexion positions (X-axis). Relative PEFR as compared with the intact stage. Error bars indicate 95% confidence intervals.

Discussion

Joint Analysis System

In the ideal experimental model, any predefined movement could be performed, and at the same time measures for force and position changes registered. All movements not predefined and incorporated in the experiments should occur unconstrained without influence on the force- and position measurements.

Previously reported experimental models for biomechanical investigation of the elbow were all constructed for kinematic testing with dynamic flexion-extension movements.[2,31,65]

Sojbjerg *et al*[65] manually applied the flexion-extension, and both valgus-varus and rotatory forces were held constant by real-time monitoring and subsequent manual corrections. In that set-up, joint compression force could not be applied, and position changes were registered by potentiometers.

An *et al*[2] applied valgus-varus force by gravity due to rotation of the set-up in between tests, and joint compression forces were applied by weights connected to tendons. In their method, rotatory forces were applied manually prior to the tests and flexion-extension was performed manually.[2]

King *et al*[31] let pneumatic actuators generate joint compression forces through connections to tendons, the same mechanism generating flexion-extension forces. In their study, valgus-varus force was created by gravity (as reported in An *et al*'s model), and rotatory forces were applied manually in between the kinematic testing.[31] The latter two models registered position changes by a three-dimensional electromagnetic tracking system[2,31], whereas the model used by Søjbjerg and others was fitted with mechanical potentiometers and strain-gauges.

The JAS is the first set-up with active control of joint compression forces, valgus-varus forces, and joint translation in the joint. Furthermore, it allows measurements on movements in the three axes and in rotation, as well as measurement of the force needed to perform the PEFR. The model does not allow measurement of valgus-varus movement, and changes in joint flexion are performed between the testing. Hence, the JAS is able to perform fully reproducible measurements without any manually applied forces; non-manually technique being shown in a prior study to improve reproducibility in a kinematic study.[26]

In Study 1, we experienced a problem with experimental reproducibility following dismounting and remounting the forearm in the cylinder in order to change the supination-pronation position. This procedure may serve as another example of decreased reproducibility due to manual performance. This particular problem was avoided in Studies 2 and 3 however, as the specimens were only tested in supination.

Dislocation mechanism and the osseous constraint

The term PEFR was introduced in order to designate specifically the combined (*en bloc*) pathological external rotation of the forearm. This may help to distinguish the phenomenon from the (physiological) supination movement, which is solely a rotation of the radius. Previous authors described an identical mechanism both in experimental studies[7,47,62] and in a clinical study.[51]

We used PEFR in our experimental model as the only applied movement so as to achieve a simple posterior joint dislocation. In the same time, the axial and joint compression forces were kept constant independently of all other factors. Without PEFR the experimental set-up remained in a steady state. Hence, in our set-up the PEFR was a necessary movement for the dislocation to occur, as stated in our hypotheses. Hyperextension as a part of the dislocation is still not investigated.

In contrast to previous studies of the dislocation[47,62], we did not consider valgus force as mandatory. The clinical test for PLRI[45], which includes valgus force, might have influenced O'Driscoll *et al* [47] when introducing valgus force as a facilitating factor in the posterior elbow dislocation. These authors explain the valgus force as a result of the *in vivo* fall on the outstretched hand.[47] As the force needed for PEFR increased following application of valgus force, and decreased following application of varus force in our first study, we tend to consider valgus force as a stabilising factor in relation to PEFR and thereby to dislocation. The phenomenon seems to be explained as an increased resistance to translation in the radiocapitellar ball-and-socket joint following increased compression (or valgus) force.[60]

Changes in joint flexion position influenced the osseous constraint to PEFR substantially, but the magnitude of change depended on the different measures. The work of the rotation until maximal torque proved more sensitive to flexion than the isolated maximal torque (Figs 6 and 7). When combining the results of the two parameters, the common lowest point of torque/work, was in the area of 10-30 degrees of flexion. Therefore, this elbow flexion angle might be the most susceptible for dislocation in relation to the osseous constraint.

The fact that the elbow seems more resistant to PEFR in the pronated position (although insignificant) has also been observed in previous clinical and experimental studies.[7,10,45,47,49] This suggests that a dislocation in the pronated position is unlikely. It may be speculated that an elbow dislocation by PEFR in forearm pronation would only occur if the pronator muscles were strong enough to maintain the pronated position in spite of rotatory forces strong enough to disrupt the LCLC. Being the more stable position, pronation is advised during immobilization of ligament deficient elbows.[7,10,42,45] One explanation for the increased stability may be that the rim of the radial head concavity is highest at one particular point.[24] In pronation, this point of the radial head has to be translated off the capitellum before occurrence of PEFR and dislocation.[24]

Without considering the capsuloligamentous constraint, it seems that supination, varus force, and flexion angle of 10-30 degrees may be facilitating factors for the posterior dislocation to occur. Furthermore, PEFR may be mandatory for the simple dislocation to occur.

Capsuloligamentous constraint

The PEFR measured initially in all uninjured specimens describes the inherent translation (PEFR) in the intact elbow joint. However, considering the relatively high mean age of the donors, and possible injury to the specimens from the preservation and preparation procedures, we do not know if a translation of equal magnitude is present in the general population, and especially in children and youngeradults. Furthermore, tension from muscles seems to increase joint stability *in vivo*.[10] In our studies, the introduction of the initial PEFR measurement on intact joints serves as a measure for baseline instability, and makes each specimen its own control during subsequent statistical analysis.

The LCLC as the prime stabiliser for rotational stability has been suggested previously.[7,20,25,39,49,51,65] Only recently however, was it suggested that insufficiency of the LUCL as well as the LCL are prerequisites for the occurrence of PLRI.[9,17,49] This concurs with our results. In relation to PEFR we also found a synergistic stabilising effect to PEFR of the anterior joint capsule when the joint is fully extended. This finding has not previously been reported, but Morrey *et al*.[38] did report stability from the anterior capsule to valgus/varus stress. Nielsen *et al*.[44] found no effect on joint laxity after capsular incision, but due to the experimental set-up these authors were not able to detect changes in laxity in the extended joint position. As the fibers in the capsule are observed to be multidirectional, any forearm rotation (except for the joint instability in the intact state as quantified in Study 2) is prevented in the fully extended joint with a tightened anterior capsule. The same phenomenon can be speculated as the reason for the previously reported stabilising function to valgus stress.[38] The clinical significance may be minor as a reconstruction of the capsule seems technically difficult and because it would improve the stability in the extended position only.

In 1985, Morrey and An[39] introduced the term Lateral Ulnar Collateral Ligament (LUCL) for the posterior part of the Lateral Collateral Ligament (LCL). O'Driscoll *et al*[45] and other authors[38] believed this ligament to be the prime ligamentous stabiliser to PEFR[42], and that restoration of the LUCL part of the lateral collateral ligament complex to be the operation of choice for PLRI or recurrent elbow dislocations. Other authors recommended a repair of the entire LCL.[7,19,42,50,51] We chose to divide the LCLC into an anterior and a posterior part relative to the radial axis, as we were not able to define the LUCL and LCL separately in our specimens. Nor were we able to detect any functional difference between the anterior and posterior parts of the ligament complex in relation to PEFR, as both had to be incised before any increased PEFR could be observed. Therefore, we see the LCLC as one structure functionally, and our study does not justify the subdivision of the ligament. Similarly, Olsen *et al*.[49,50] reported the LCLC to be a complex structure, being unable to identify discrete bands anatomically or functionally. Also Imatani *et al*.[23] and Cohen and Hastings[7] believed that the LUCL contributes to, rather than is, a major constraint to PLRI, the former authors having difficulty in defining the LUCL by microscopy.[23,49]

We found the MCL to be without influence on PEFR in the osseous intact joint. In contrast to a previously suggested dislocation mechanism[47], the MCL had to be sacrificed in our study before occurrence of a complete posterior dislocation. During the experiments it was proved that the MCL prevented the posterior translation of the forearm after the PEFR had rotated the coronoid process away from the trochlea.

Consideration of the capsuloligamentous constraint, as found in our study, in relation to the posterior dislocation mechanism does not contradict the speculated facilitating factors mentioned in the previous section concerning the osseous constraint. Actually, if the elbow is impacted by axial force, varus stress, and external rotatory force, it seems from Study 2 that the LCLC is the only initially acting ligamentous stabiliser against posterior dislocation.

Osteoligamentous lesions

Clinically relevant combined osteoligamentous lesions were selected for Study 3. Due to the nature of these sequentially performed experiments, we also gained information regarding the isolated structures as restraints to PEFR. The RH is considered to be important for rotational stability, but we found that the magnitudes of PEFR increase in virtually a similar manner following RH and CP excision, respectively. In a study not incorporating joint compression forces, Jensen *et al*[25] likewise observed increased joint laxity in relation to external rotation after RH excision, and proposed a slackening of the LCLC as the mechanism responsible. During our experiments, we also noticed slackening of the LCLC after RH excision. Therefore the RH may maintain rotatory constraint by a tensioning of the LCLC. In contrast, Morrey *et al*[41] reported that the RH could be resected without altering joint stability, though these authors did not investigate stability to forced external rotation.

The coronoid fracture Stage II acted independently as constraint to PEFR in our study. Other authors conclude that elbows with a fracture greater than 50% of the coronoid height more readily displace when an axial load is applied.[6] Both studies indicate that a Stage II coronoid fracture (or worse) induces both axial and rotational instability in the joint. This correlates with findings in a clinical follow-up study on elbow joint dislocations, where recurrent dislocations related to the presence of coronoid fractures[27]. Operative reconstruction of even small coronoid fractures is advised in a recent study, as this is considered to be an important restraint to redislocation.[66] Our pilot study did not reveal PEFR increase after a Stage I fracture, but our main study supports the suggestion that a Stage II fracture in an instable elbow should be reconstructed, if possible.

Combined CP fracture and RH excision increased laxity dramatically. RH prosthetic replacement improved laxity in two ways. Firstly, the joints no longer subluxated as the prosthesis kept the forearm from translating posteriorly in relation to the distal humerus because the prosthesis restored the radio-capitellar contact. Secondly, the dramatic increase in PEFR induced by the two fractures almost normalised (Fig. 12). Although such combined fractures without ligamentous damage would seem most unlikely in vivo, the experiment highlights the specific effects of the two fractures alone and in combination, as well as the prosthetic replacement in relation to PEFR and posterior elbow dislocation.

Our study suggests that either the CP or the RH must be present (the CP more than 50% of the original height) in order to prevent posterior translation of the forearm, even with the collateral ligaments intact. The other condition for restraint to gross PEFR, and thereby to dislocation, was a functioning LCLC (intact or reconstructed) regardless of RH (intact or prosthesis) or CP presence.

We combined experimental fractures with ligamentous injuries in order to mimic clinical situations. One combination corresponds to the clinical situation following dislocation of the elbow with rupture of all ligaments and loss of RH support due to comminuted fracture, but with an intact CP. The insignificant changes in PEFR (Fig. 13) indicate that the method of LCL reconstruction reported by Morrey *et al*.[40] and Nestor *et al*[42] provides a good restraint to PEFR, even with an excised RH and a damaged MCL. Several authors have suggested use of RH prosthetic replacement.[14,18,31,53] The present study indicates that use of a LCLC plasty avoids gross instability, even without implantation of a RH prosthesis.

Severance of the MCL following the double fracture, the LCL reconstruction, or the RH prosthesis resulted in a slight (but in our study insignificant) increase in PEFR. After this MCL incision, we noticed an increased carrying angle (valgus displacement) in the starting position before each test. This concurs with a previous study emphasising the importance of the MCL in elbows with valgus instability.[41]

We have not investigated soft tissue structures except for the ligaments. Other studies suggest that restraint to PEFR and dislocation may be contributed from tendons and muscles that will still function normally during a state of PLRI or after a dislocation, either as direct support[7] or by compression forces.[10] An increased stability by compression force seems reasonable, though we have only pilot study data to support this.

Conclusion

The previously presented hypothesis regarding the joint dislocation mechanism is supported by our experiments. In our experimental set-up the combination of supination, flexion of 30 degrees, and varus stress facilitates the posterior elbow joint dislocation, which is a result of pathological external forearm rotation (PEFR) and axial compression. Our experiments underline the primacy of the LCLC as constraint to PEFR and subsequent joint dislocation as well, whereas the third hypothesis regarding the secondary constraints does not concur with our results. The radial head, the coronoid process, and the anterior capsule (the capsule in the extended joint position only) were found to be primary constraints, as isolated insufficiency of each of these structures increased joint laxity to PEFR. The MCL was not a constraint to PEFR or to dislocation in the isolated MCL-insufficient joint, but MCL had a minor stabilising effect when other injuries were applied, and therefore the MCL does act as a secondary constraint. LCLC reconstruction in the joints suffering the "Terrible Triad" nearly re-established stability to PEFR in accordance with our last hypothesis, but additional restoration of either the radial head or the coronoid process as constraint to proximal ulno-humeral dislocation to avoid dislocation was necessary as well .

Clinical relevance

The results of our studies support the view that the instable elbow should be immobilisated in the pronated position in order to reach maximal stability to redislocation. In the same context, the specimens show least stability when supinated, and this supports the clinical investigation of radio-humeral instability by the posterolateral stress test (PST), which is performed during supination. Thus, posterolateral instability is diagnosed with the least necessary force. We suggest the PST to be performed during neutral or varus stress during forearm supination and elbow flexion, because this decreases the needed force for dislocation of the radial head compared to valgus stress. Furthermore, the torque needed torque to perform PEFR increased with joint flexion angle, which suggests that the elbow dislocation mechanism occurs more easily in a semiflexed position. The semiflexed position is incorporated in the PST, and if any preventive measures should be taken against accidents leading to dislocation they should focus on protection of the semiflexed arm.

This study supports the method of operative reconstruction of the LCL as currently used in Århus University Hospital, and it suggests use of the method even in cases with an absent radial head. This procedure has been performed recently in our clinic as well

An important role of the anterior capsule as a primary stabiliser in the fully extended elbow is indicated; the anterior capsule should therefore be left as intact as possible after operative procedures.

The lateral collateral ligament complex is one structure functionally, and our study does not justify the subdivision of this ligament during operative procedures; stability will be maintained even though part of the ligament is damaged or incised peroperatively.

Coronoid fractures Stage II or worse should be reconstructed, if possible. In a situation with insufficiency of the radial head, such a reconstruction is necessary to establish stability to dislocation. If reconstruction is impossible, a radial head prosthesis keeps the forearm from translating posteriorly in relation to the distal humerus because the prosthesis restores the radio-capitellar contact.

The “minimum procedure” (LCL-reconstruction and radial head prosthetic replacement) of the “Terrible Triad” may provide sufficient restraint against gross posterolateral elbow joint laxity and redislocation *in vivo*.

Future studies

1. A prospective clinical study of elbow joint dislocations with follow-up is desirable. Clinical and MRI findings in the acute stage should be correlated with long-term results. In relation to joint instability this might uncover new findings as risk factors of undesired long-term effects. Furthermore, it would classify the MRI as a possible recommended future method of elbow joint investigation in the acute stage for evaluation of soft tissue damages, which again may support a decision regarding surgical treatment. Such study would allow evaluation of the current standard of regional treatment of elbow dislocation, and possibly raise the standard due to increased attention. Lastly, epidemiological risk factors concerning accident and injury mechanisms might appear. The Department of Radiology, MRI-section, Århus University Hospital has recently decided to conduct a standard MR-investigation of the collateral elbow ligaments; this could be applied to such a study which is planned to include patients from the counties of Northern Jutland.
2. Partly as a consequence of our findings, the Department of Orthopaedics, Shoulder and Elbow Section, Århus University Hospital has performed a tightening procedure of the LCLC in patients with grossly comminute radial head fractures suitable for RH-excision in order to increase the LCLC restraint to PEFR. A randomised prospective study where this procedure is performed on one group, and RH prosthetic replacement (absorbable RH prosthesis?) is performed on another group, would clarify the long-term outcome regarding stability, arthritis, pain etc.
3. As a part of the clinical prospective study mentioned above, the group of patients suffering the "Terrible Triad" may be treated according to a distinct algorithm, which could be partly decided on the basis of the results in this thesis: repair of the lateral column of ligaments only and reconstruction/replacement of the RH alone even in situations with an insufficient CP, or isolated CP and LCLC repair in order to minimise the surgical approach.

Summary

This Ph.D.-thesis is based on three experimental studies performed at the Orthopaedic Research Laboratory, Århus University Hospital, Denmark. Three manuscripts are published internationally.

Aim.

To evaluate the trauma pathokinematics and the inherent joint stability of the human elbow joint in relation to posterior joint dislocation. Three series of experiments involved:

1. Determination of the flexion position of the osseous joint with the least constraint to external forearm rotation, a generally accepted condition for dislocation to occur.
2. Evaluation of the isolated capsuloligamentous structures as constraints to posterior dislocation.
3. Evaluation of the effect on stability of combined osteoligamentous lesions following dislocation, and of clinically used reconstructive procedures as well.

Methods.

A total of 36 human elbow joint specimens were tested in a new Joint Analysis System (JAS) able to simulate the posterior dislocation. Simultaneously, the JAS allowed control of joint compression forces and pathological movements in the joint, and collected data of both position changes and forces impacting the joint.

In Study 1, elbow joint specimens without soft tissues were used under change of joint flexion position, valgus-varus stress, and supination-pronation position. Sequential section of capsuloligamentous structures followed by stability tests was performed in Study 2. Typical fractures after dislocation were applied on the specimens in Study 3, alone or in combination with ligamentous damage and radial head prosthetic replacement or lateral ligament reconstruction. Stability tests determined effects of injuries and reconstructive procedures.

Results.

The osseous stability, expressed as the maximal torque needed for external forearm rotation, increased from varus to valgus stress (p=0.0001), from 10 to 90 degrees of elbow flexion (p=0.012) and also tended (non-significantly) to increase from forearm supination to pronation. The work needed to reach this point of maximal torque was least at 30 degrees of flexion, and increased with both further flexion and further extension. The conditions of the elbow in a slightly flexed position and varus stress seemed, combined with a forearm external rotation trauma, to be the important biomechanical factors in posterior elbow dislocation in relation to the osseous constraint.

The primary stabilizers against external forearm rotation in the extended elbow were the anterior capsule and the lateral collateral ligament complex (LCLC), whereas in the flexed elbow the anterior capsule did not have stabilizing effect. In flexed joint positions, the LCLC seems to be the only capsuloligamentous stabiliser against external forearm rotation and thereby against posterolateral instability and ultimately against

posterior dislocation. The LCLC appears to be one functional unit, as we found no separate stabilizing function of either the lateral ulnar collateral ligament or the lateral collateral ligament. The medial collateral ligament is not a restraint to pathological external forearm rotation, but it had to be sacrificed with all other ligaments and the entire capsule before a complete experimental elbow joint dislocation occurred.

Both the radial head and the coronoid process act as independent restraints in relation to external forearm rotation in our experimental set-up. When both are fractured, the joint subluxates regardless of intact collateral ligaments, and in our study the subluxation was terminated by insertion of radial head prosthesis which also virtually normalized the laxity to external rotation. Lateral collateral ligament reconstruction and insertion of radial head prosthesis to the "Terrible Triad" yielded restraint against gross joint instability in our experimental set-up.

Summary in Danish (Dansk resume)

Ph-d afhandlingen baseres på eksperimenter udført på Ortopædisk Forskningslaboratorium, Århus Universitetshospital. Tre internationale artikler publiceres.

Formål.

At belyse patokinematikken i den posteriore albueluksation og de enkelte ledstrukturers betydning for stabiliteten imod luksation, herunder i tre delstudier at:

- bestemme den position i fleksionsbuen, hvor modstanden i det ossøse præparat mod udadrotation af underarmen en bloc (patologisk underarms udadrotation) er mindst, idet udadrotation forudsættes at være et nødvendigt trin i luksationsprocessen.
- på baggrund af ovenstående observationer og ved sekventielle ligamentlæsioner påvise hvilke ligamentære stabilisatorer, der modstår patologisk underarms udadrotation og luksation.
- evaluere de ved luksatonen typiske frakturers betydning for stabiliteten i kombination med skader på de i delstudie 2 fundne ligamentære stabilisatorer.

Metode.

Humane albuepræparater blev undersøgt i et nyudviklet ledanalysesystem som simulerede patokinematikken i den posteriore albueluksation. Systemet kunne samtidig opretholde konstante ledkompressionskræfter, samt måle og digitalt registrere tredimensionelle positions-, moment- og kraftændringer i leddet. Det rent ossøse leds modstand mod patologisk underarms udadrotation under skiftende ydre kræfter, de enkelte capsuloligamentære strukturers betydning for stabiliteten imod patologisk underarms udadrotation, og endelig kombinerede ossøse og ligamentære skaders betydning for stabiliteten før og efter rekonstruktion, blev kvantificeret i tre delstudier inkluderende ialt 36 præparater.

Resultater.

Det maksimale moment som kræves til luksation ved patologisk underarms udadrotation mindskes ved ekstension, varus stress og pronation. Det samlede arbejde der skal tilføres underarmen for at nå punktet med maksimalt krævet moment er mindst ved ledflektionsstilling omkring 30 grader. Disse faktorer kan være af betydning for stabiliteten i albuen imod luksation.

Det laterale kollaterale ligament kompleks er den vigtigste ligamentære stabilisator mod patologisk underarms udadrotation, denne funktion er dog understøttet af forreste ledkapsel i strakt stilling af leddet. I flekteret stilling er der ikke effekt af den forreste kapsel, og den bagre kapsel fandtes betydningsløs mht patologisk underarms udadrotation. Både funktionelt og anatomisk fremstår det laterale kollaterale ligamentkompleks som en helhed uden selvstændig funktion af det tidligere definerede laterale ulnare kollaterale ligament eller af det laterale kollaterale ligament. Det mediale kollaterale ligament fandtes ikke at have indflydelse på patologisk underarms udadrotation. Inden en komplet posterior luksation kunne forekomme i opstillingen måtte alle ligamenter og hele ledkapslen incideres.

Caput radii og processus coronoideus har begge en selvstændig betydning for stabiliteten, og ved fraktur af begge vil leddet subluksere uafhængigt af intakte kollaterale ligamenter. Subluksationen kunne i vores set up neutraliseres med en caput radii protese. En i klinikken anvendt metode til ligamentrekonstruktion af det laterale kollaterale ligament kompleks viste sig sufficient mht patologisk underarms udadrotation, og denne ligamentrekonstruktion kunne også anvendes selvstændigt efter excision af caput radii til at stabilisere leddet imod større instabilitet. Rekonstruktion af det laterale kollaterale ligament kompleks og indsættelse af caput radii protese, som minimalbehandling af den maximalt instabile situation, kunne ligeledes anvendes til opnåelse af stabilitet imod luksation.

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Manuscript I

Elbow Joint Stability In Relation To Forced External Rotation:

An Experimental Study of the Osseous Constraint

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Abstract

The objective was to evaluate the osseous constraint related to forced forearm external rotation as the initial stage in a posterior elbow dislocation. Six joint specimens without soft tissues were examined in a joint analysis system developed for simulation of dislocation. The osseous stability, expressed as the maximal torque needed for pathological external forearm rotation, increased from varus to valgus stress (p=0.0001), from 10 to 90 degrees of elbow flexion (p=0.012) and also tended to increase from forearm supination to pronation. The work of the pathological external forearm rotation until the point of maximal torque decreased from a maximum in full extension to a minimum at 30 degrees of elbow flexion (p=0.03). The elbow in a slightly flexed position, varus stress, and a forearm external rotation trauma, might be the important biomechanical factors in the posterior elbow dislocation, and they might serve as guidelines during clinical investigation for posterolateral instability.

Introduction.

Elbow joint dislocations are mostly posterior, but the mechanism of the posterior dislocation is sparsely elucidated, and the results are discrepant.[14,14,17,22,22] Osborne and Cotterill (1966) were the first to suggest a pathological external forearm rotation as the initial step of the posterior elbow dislocation.[17] This is illustrated as Pathological External Forearm Rotation (PEFR) in Fig. 1.

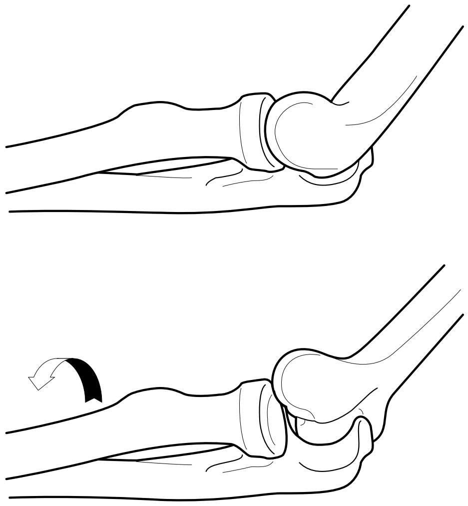

Figure 1.

The mechanism of the Pathological External Forearm Rotation (PEFR): The lower drawing illustrates the simultaneous radiohumeral dislocation and ulnar external rotation during the initial PEFR.

PEFR is a combined rotation of both forearm bones relative to the humerus, and should be distinguished from the forearm supination-pronation position, which is movement of the radius relative to the ulna. PEFR results in a radiohumeral dislocation as the radial head is translated off the capitellum, and a simultaneous rotation of the ulna in the trochlear groove. This may reduce the stabilising effect of the coronoid process against posterior dislocation when an axial force impacts the ulna. In an experimental study Sojbjerg et al.[22] reported external rotation and valgus moment at 30° to result in elbow dislocation, but axial force was not investigated. O'Driscoll et al.[14] suggested that dislocation results from external rotation (34°-50°) and valgus moment with axial force at 80° of joint flexion.

The osseous stability in relation to PEFR may be important in both elbow dislocation and posterolateral rotatory instability (PLRI). PLRI may be seen after a simple sprain or after posterior subluxation or dislocation, being the most common pattern of elbow instability.[14] Several studies have investigated the ligamentous role of stability to PLRI [2,3,3,12,12,13,13,15,15] but they do not define the pure osseous stability relative to PEFR. Other studies concerned with the stability of the elbow joint discuss the inherent osseous stability, but it is never quantified systematically.[1,1,5,10,10,11,19,19]
To simulate the posterior elbow dislocation under simultaneous control of joint compression forces and pathological movements of the joint, we developed a Joint Analysis System (JAS). The aim of the present study was to evaluate the osseous stability of the elbow joint in relation to PEFR in different joint positions and with different forces impacting the joint.

Materials and methods

Joint Analysis System. The JAS is a computer controlled test system working in the three dimensions of a coordinate system (X, Y and Z), with rotation (R) possible about the X-axis (Fig. 2).[6] The humerus is mounted on a platform, which permits horizontal movement in any direction in the X-Z plane. The elbow flexion (F) is preset and changed prior to each test by tilting the humeral fixator about the Z-axis. The cylindrical fixation device for the forearm is mounted horizontally on a vertical pillar, which provides vertical movement for the horizontally positioned forearm along the Y-axis (Y). In the cylinder, the forearm can be rotated about the X-axis. The forearm fixation device is constructed to allow free movement in the horizontal plane about a vertical axis perpendicular to the forearm, and centred through the deepest point of the ulnar joint surface. The system thus allows the forearm to swing unconstrained horizontally during a test. Furthermore, we are able to apply a constant varus or valgus torque to the joint by a winded steel wire (Fig. 2).

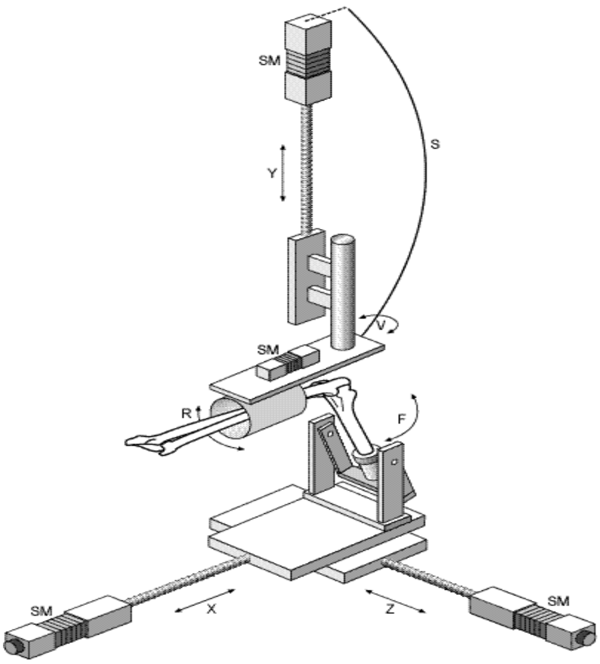

Figure 2.

The Joint Analysis System (JAS) with a specimen mounted. The axes of linear movement are marked X, Y and Z, and PEFR rotation about the forearm is marked R. These movements are controlled by stepping motors (SM). F denotes elbow flexion, which is preset, and V is the free horizontal (valgus-varus) movement. The steel wire for applying valgus-varus stress is marked S.

The system is controlled by a personal computer equipped with the LabVIEW® software (National Instruments®, Austin, Texas). The computer controls switch units (Berger-Lahr®, Germany) for four step motors (Berger-Lahr®, Germany), each providing the movement along one of the linear axes or the rotation about the X-axis. The system permits movement in steps of 5 µm in the XYZ-coordinate system and in steps of 0.037° of forearm rotation, and works with a speed of approximately 80 steps per second. To collect data regarding the forces impacting the joint, one pair of strain gauges is mounted on the fixation unit corresponding with each axis and rotation. By four amplifiers custom made at our laboratory, the computer collects real-time data of the force from all four sets of strain gauges and movement data from the four step motors. Data are saved in a log file. The JAS allows force measurement with a precision of 0.01 N in the three linear axes and in rotation. It is calibrated with weights prior to specimen mounting. In a validation test, five repeated measurements of two specimens not previously tested gave means with a standard error of 1.3% and 1.4%, respectively.

Specimens. The investigation involved six fresh frozen upper extremities (three left and three right) from six males with a median age of 79 years (range 75-84), all specimens being resected through the mid-humeral and mid-metacarpal levels. All soft tissues were removed, leaving only the interosseous membrane and the annular ligament intact. The specimens were examined prior to inclusion and showed no sign of joint pathology. To mark the elbow flexion axis, a Kirschner wire was drilled through the trochlea in the axis of elbow flexion. This axis lies through the centers of the arcs formed by the trochlear sulcus and the capitellum.[9] Before mounting the forearm in the JAS, the fixed supination-pronation position was secured with a 3.5 mm cancellous screw at the radial neck level transfixing the ulna and the radius in the chosen position. The forearm was then positioned in the center of the cylinder (Fig. 2) and secured with screws against the bones from multiple directions. When the supination-pronation position was changed between the tests, the forearm was dismounted from the cylinder, and the cancellous screw repositioned. The axis of the PEFR was chosen as a line from the center of the proximal radioulnar joint to the center of distal ulna, because axial force from the forearm is transmitted to the humerus almost equally through radius and ulna.[4] This axis was centered in the cylinder, thereby being the forearm PEFR axis when the cylinder was mounted in the JAS. The humerus was fixed in the JAS as seen in Fig. 2. The articular surfaces were kept permanently moist with physiological saline solution.

Experimental protocol. Constant factors during all tests were a forearm axial force of 15 N (along the X axis), and a joint compression force of 5 N perpendicular to the forearm thereby acting vertically downwards (along the Y axis). Both forces were relatively minor to avoid damage on the joint surfaces during the tests. The Z force was automatically kept within 0± 0.25 N during all tests. Variable factors were joint flexion (0, 10, 20, 30, 45 and 90°), forearm supination-pronation position (maximal supination, neutral, maximal pronation), and valgus-varus torque ($2.25*10^{-3}$ Nm). Hence, each specimen was tested in 54 different combinations of the variable factors.

The maximal joint congruence in each position was defined as the start position. This was reached by manually moving the joint along the X- and Z-axes and in rotation until the deepest joint position on the Y- and X-axes were measured. During each test, the JAS applied the constant forces to the joint as the first step. It then, performed the PEFR in a stepwise manner (0.037°/step), and for each step collected simultaneous data of both position and force from the three axes and from the rotation. Each test was manually terminated when the ulnar angular movement resulted in coronoid process dislocation posteriorly in the trochlear groove.

Data analysis. The torque (Nm) applied to the forearm was calculated as the measured rotational force (N) times the cylinder radius (0.044 m). The maximal torque value was defined as the highest moving average of 10 measurements. The total work needed to reach the point of maximal torque was calculated as the angle of rotation (radians) times cylinder radius (m) times the average force measured (N) in ten step intervals.

The statistical analysis was performed using a variance component model as described in the Proc Mixed procedure,[8] and the SAS™ (SAS Institute Inc., Cary, NC, USA) statistical software. The total variance of data was divided in variances of the changing factors in the tests (stress, supination-pronation position, flexion angle, and specimen number). All factors and all effects of random interactions, for example stress×flexion, were tested for significant influence. All non-significant interactions were neglected in subsequent analyses. Lastly, the magnitude of factor influence on maximum torque, rotational work and rotation were calculated. P-values less than 0.05 were considered significant.

Results

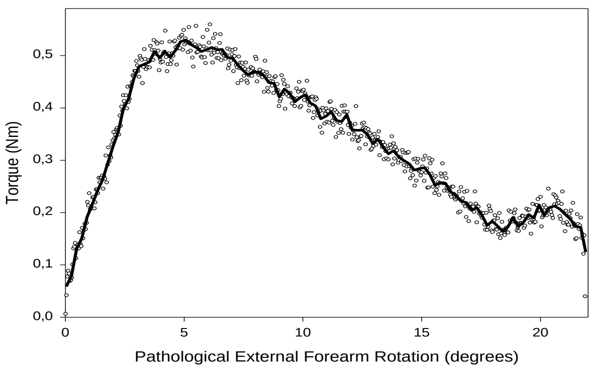

Figure 3.

A typical curve of PEFR angular displacement versus the rotatory torque. The X-axis is rotation in degrees, and the Y-axis is the torque in Nm.

In all tests we noticed the maximal torque value during the PEFR to occur early, as illustrated in Fig. 3, which shows a typical curve of the torque versus the angular displacement during the PEFR. At this point, the radial head was still articulating with the capitellum. From the point of maximal torque until the coronoid process had passed the trochlea posteriorly and the dislocation was complete, the torque fell to a much lower level. Fig. 4 depicts the mean maximal torque needed for the PEFR in the 54 different test situations.

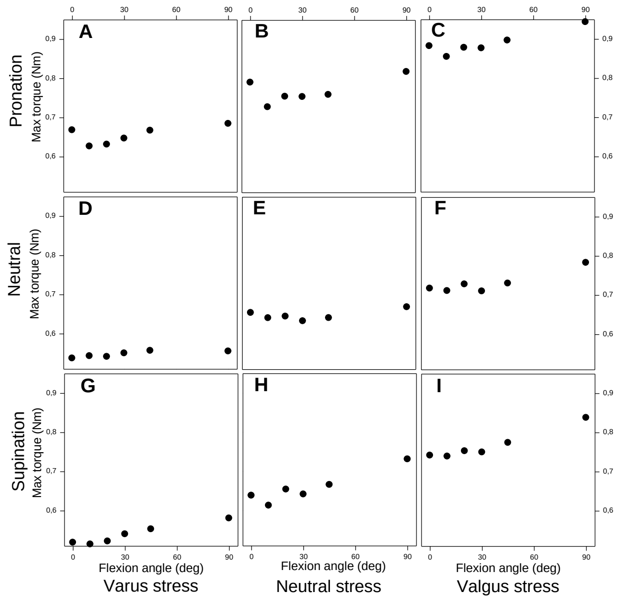

Figure 4

Mean maximal PEFR torque versus flexion angle, shown for type of joint stress and supination-pronation position respectively. The forearm is in the pronated position in the upper row (ABC), neutral in the middle row (DEF), and in supination in the lower row (GHI). Varus stress is applied to the elbow in the left column (ADG), neutral stress in the middle column (BEH), and valgus stress in the right column (CFI).

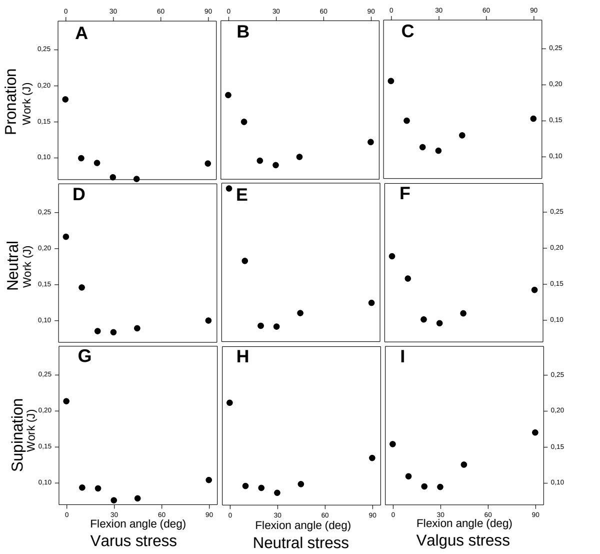

Figure 5

Mean forearm PEFR work until the point of maximal torque versus flexion angle, shown for type of joint stress and supination-pronation position. See legend in Fig.4 for details.

The torque increased from varus stress to valgus stress by 35% (p=0.0001), and it generally increased from 10° towards 90° of flexion by 17% (p=0.012). In our series it also tended to increase from supination to pronation, but the change was non-significant (p=0.1). Thus, the osseous stability expressed as the maximal necessary torque for PEFR fell to a minimum in the slightly flexed elbow exposed to varus stress and with the forearm in supination, and reached a maximum in the 90° flexed elbow exposed to valgus stress and with the forearm in pronation. The total work of the PEFR, until the point of maximal torque was reached, decreased from a maximum in full extension to a minimum at 30° of flexion in nearly all combinations of valgus-varus stress and supination-pronation position, as shown in Fig. 5 (p=0.03). Valgus-varus stress and supination-pronation position did not influence the work (p=0.42 and 0.79).

Discussion

Two previous experimental models have simulated joint compression forces during elbow joint movement.[7,11] Johnson et al.[7] compared the reproducibility of the joint kinematics in passive and active testing of the intact elbow joint using a compression-movement-controlled model. Pneumatic actuators generated the joint compression and joint movement, and the authors concluded that active control of movement compared to passive (or manual) movement of the joint increased the reproducibility of the joint kinematics measurements. In a study investigating the constraints of the elbow to valgus stability, Morrey et al.[11] presented a model that generated joint compression forces by weights, but joint movement was performed manually. Both studies investigated kinematics of the elbow joint and did not specifically consider osseous joint stability in relation to forced rotation.

We here present a model with active control of joint compression forces, valgus-varus forces, and the patokinematic PEFR-movement in the joint. The model also measures the force needed to perform the PEFR which is considered to be the first step of posterior elbow dislocation,[14,17,17,22,22] and furthermore to be the possible trauma for development of posterolateral elbow instability.[13,20] [13] If the PEFR should occur during forearm pronation, the pronator muscles should to be powerful enough to prevent forearm rotation to the supinated position when an outward rotational trauma impacts the hand. Such a patomechanism seems unlikely, but we wished to elucidate the general osseous constraints of the elbow joint to PEFR, also during immobilisation, and therefore decided to test our specimens not only in supinated position but also in neutral and pronated position.

In all tests in our study, the point of maximal torque during PEFR was reached at a point prior to radiohumeral dislocation. We focused our analysis on this point, because further rotation until complete ulnohumeral dislocation required much less torque. We found the maximal torque for PEFR to be dependent on joint stress, as the specimens were most stable with respect to PEFR during valgus stress, and least stable during varus stress (Fig. 4). With neutral joint stress, approximately 50% of an axial force from the forearm to the humerus passes through the radiohumeral joint.[4] An even larger part of the axial force is transmitted through the radiohumeral joint during valgus stress. This situation makes the joint more resistant to translation, due to increased compression in this ball and socket shaped joint.[21] The aforementioned seems a reasonable explanation of the findings of our study.

Various authors agree that the elbow is most resistant to lateral rotational instability in the pronated position[2,13,16].[2,13,14,16] On the other hand, a recent study by Pomianowski et al[18] suggested that the elbow is least stable to valgus-varus stress when pronated. When pronated, the osseous elbows in our study tended to be most stable relative to PEFR, but we do not know if this relates to valgus-varus stability. Our data analysis disclosed a problem of an imprecise centering of the specimen in the cylinder after a change in the supination-pronation position. This would alter the distance from the rotational axis to the radial head and thereby influence the measured torque. If this factor was neglected in data analysis, the rotation also influenced the torque ($p<0.05$). Even though our study only focuses on the osseous constraint, our results therefore are in agreement with previous studies advocating for elbow immobilisation following a posterolateral dislocation in the pronated position[12,13].[2,12,13] Our specimens showed least stability when supinated, and this concurs with the clinical investigation of radio-humeral instability by the posterolateral stress test (PST), which is performed during supination. This way, posterolateral instability is diagnosed with the least necessary force, and the patient might be subjected to the least necessary pain. In the same context, the torque in PEFR increased with joint flexion angle ($p=0.036$), which suggests that the elbow dislocation mechanism occurs more easily in an extended or semiflexed position. The semiflexed position is concurringly incorporated in the PST.

In contrast to torque, the rotational work needed to reach the point of maximal rotatory torque during PEFR seems very dependent on elbow flexion angle, as the mean work at full extension is almost tripled compared to 30° (Fig. 5). This is seen in Figs. 4 and 5, as the generally straight shape of the curves in Fig. 4 is very different from the L-shaped curves in Fig. 5. Our data analysis revealed the PEFR angle at maximal torque to correspond well with the work of the PEFR until this point. This indicates that the rotational work in our study is mainly dependent on the differences in the PEFR angle at maximal torque. This is in agreement with the formula for the work: Work=distance×force, as distance is angular displacement in PEFR and force corresponds to the measured torque. The studies concerning elbow dislocation mechanism describe flexion angles of 30°[22], “incompletely extended”[17], and 80°.[14] Our results indicate the initial part of the PEFR to take place with the least required work at 30°. In relation to the clinic, this is another indication that the PST should be performed in slight flexion.

In conclusion, the osseous stability relative to PEFR is expressed in two parameters: Maximal needed torque of PEFR until complete elbow dislocation, and the work to perform the PEFR until the point of maximal torque. We find the torque to be minimal at 10° of elbow flexion, and the least work at 30° of flexion. Stability is increased during valgus stress and reduced during varus stress. Varus stress and elbow flexion of 10° to 30° may be facilitating factors in the elbow dislocation mechanism. The posterolateral stress test should be performed in neutral stress or varus stress in a semiflexed position in order to diagnose instability with the least necessary force.

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Manuscript II

Ligamentous and Capsular Restraints

To Experimental Posterior Elbow Joint Dislocation

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Abstract

Pathological external forearm rotation (PEFR) relates to posterolateral elbow joint instability, and is considered to be a necessary step in posterior elbow dislocation. The aim of this study was to evaluate the capsuloligamentous restraint to PEFR. Eighteen elbow joint specimens were examined in a joint analysis system developed for experimental elbow dislocation. Sequential cutting of capsule and ligaments followed by stability testing provided specific data relating to each capsuloligamentous structure. The primary stabilizers against PEFR in the extended elbow were the anterior capsule and the lateral collateral ligament complex (LCLC), whereas in the flexed elbow the anterior capsule did not have stabilizing effect. In flexed joint positions, the LCLC seems to be the only immediate stabilizer against PEFR and thereby against posterolateral instability and ultimately against posterior dislocation. The medial collateral ligament did not have any immediate stabilizing effect, but it prevented the final step of the posterior dislocation.

Keywords

Upper extremity, joint instability, fall injuries.

Introduction

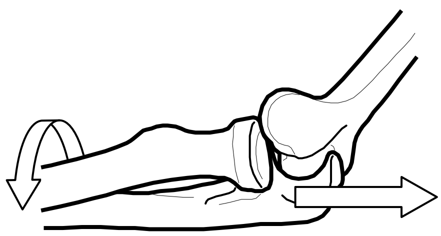

Figure 1
The elbow joint dislocation mechanism. Arrow 1 illustrates the initial pathological external forearm rotation (PEFR), and arrow 2 the posterior translation of the forearm.

The hypothesis of pathological external forearm rotation (PEFR) as a necessity for a posterior elbow dislocation to occur was originally suggested on the basis of a survey of elbow pathology in patients with recurrent elbow dislocation (Osborne and Cotterill, 1966), and the hypothesis was later supported by clinical studies.(Kinast, Wadstrom and Pfeiffer, 1986)(O'Driscoll, Bell and Morrey, 1991) In experimental kinematic studies using cadaver specimens, the external forearm rotation has been used as a part of the dislocation mechanism. (Sojbjerg, Helmig and Andersen, 1989)(O'Driscoll, Morrey, Korinek and An, 1992) The PEFR can be defined as an external rotation of the forearm complex relative to the humerus translating the radial head off the humeral capitellum. During this rotation the height and stabilizing effect of the coronoid process is reduced in relation to the trochlea. As a result, the elbow joint looses osseous stability to axial forces along the forearm. If a sufficient axial compression force impacts the joint after the axial bony stability is lost, the elbow will dislocate (O'Driscoll et al, 1992)(Deutch, Jensen, Olsen and Sneppen, 2002) see figure 1.

Even though the soft tissue contribution to stability in relation to PEFR seems important in an elbow dislocation as well as in posterolateral rotatory instability (PLRI), which is the most common pattern of recurrent elbow instability (O'Driscoll et al, 1992), only few studies have evaluated the capsule and ligaments experimentally in relation to PEFR. (Cohen and Hastings, 1997)(Olsen, Søjbjerg, Nielsen, Dalstra and Sneppen, 1998)(Hannouche and Begue 1999) (Dunning, Zarzour, Patterson, Johnson and King, 2001) Such studies included serial sectioning of capsule and ligaments, but in only one study were joint compression forces applied in the experimental set up.(O'Driscoll et al, 1992) As the elbow joint has a high congruency these compression forces may play a significant role in stability. Experimentally applied joint compression force may also simulate *in vivo* muscle forces. In the study by O'Driscoll et al (1992) it was concluded that the posterior elbow dislocation occurred with the anterior medial collateral ligament intact. This finding contrasts the clinical observations of other authors.(Josefsson, Johnell and Wendeberg, 1987)

The aim of the present study was to evaluate the capsule and ligaments as constraints to PEFR and ultimately to posterior elbow dislocation during simoultaneous application of joint compression forces in order to simulate the in vivo situation.

Material and methods

Specimens. The experiments included 18 fresh frozen upper extremities (four left and 14 right) obtained from 12 females and 6 males with a median age of 77 years (range 65-93). All specimens were resected through the mid-humeral and carpal levels. Soft tissues were removed, leaving the interosseous membrane and joint capsule with ligaments intact. The specimens were examined prior to inclusion. Only specimens without signs of joint pathology (eg arthrosis or fracture) were included.

Joint Analysis System. The Joint Analysis System (JAS) is a computer controlled test system working in the three dimensions of a coordinate system (X, Y and Z), with rotation (R) possible about the X-axis (Fig. 2)(Deutch et al, 2002). The humerus is mounted on a platform which permits

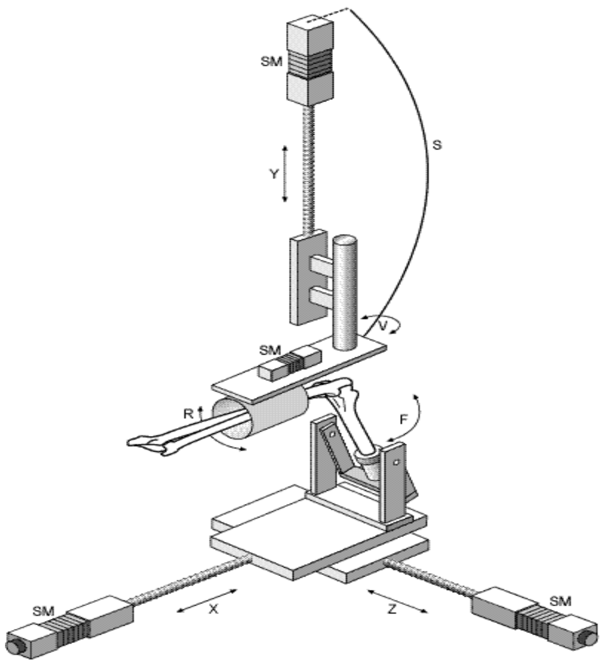

Figure 2

The Joint Analysis System (JAS) with a specimen mounted. The axes of linear movement are marked X, Y and Z, and PEFR rotation about the forearm is marked R. These movements are controlled by stepping motors (SM). F denotes elbow flexion, which is preset, and V is the free horizontal (valgus-varus) movement.

horizontal movement in any direction in the X-Z plane. The elbow flexion (F) is preset and changed prior to each test by tilting the humeral fixator about the Z-axis. The cylindrical fixation device for the forearm is mounted horizontally on a vertical pillar which provides vertical movement for the horizontally positioned forearm along the Y-axis (Y). By turning the cylinder, PEFR is performed with the forearm bones as an entity about the X-axis. The forearm fixation device is constructed to allow free movement in the horizontal plane about a vertical axis perpendicular to the forearm, and centered through the deepest point of the ulnar joint surface. The system thus allows the forearm to swing unconstrained horizontally during a test. The system is controlled by a personal computer equipped with LabVIEW® software (National Instruments®, Austin, Texas). The computer controls switch units (Berger-Lahr®, Germany) for four step motors (Berger-Lahr®, Germany), each providing the movement along one of the linear axes or the rotation about the X-axis. The system performs movement in steps of 5 μm in the XYZ-coordinate system and PEFR in steps of 0.037°, and works with a speed of approximately 80 steps per second. To collect data regarding the forces impacting the joint, one pair of strain gauges was mounted on the fixation unit corresponding with each axis and rotation. By four amplifiers custom made at our laboratory, the computer collects real-time data of the force from all four sets of strain gauges and movement data from the four step motors. Data are saved in a log file. The JAS is calibrated with weights prior to specimen mounting.

Specimen fixation in the JAS. The humerus was fixed in the JAS as shown in Fig. 2. With the elbow flexed 90° and the forearm parallel to the X-axis, the elbow flexion axis was defined and secured by locking the humeral fixator in relation to humeral rotation. The forearm was positioned in maximal supination centrally in the cylinder (Fig. 2) and secured with multiple screws against the bones from different directions. The axis of the PEFR was chosen as a line from the center of the proximal radioulnar joint to the center of the distal ulna, because axial force from the forearm is transmitted to the humerus almost equally through the radius and ulna. (Halls and Travill, 1964)(Morrey, An and Stormont, 1988) This axis was centered in the cylinder, thereby being the axis of PEFR when the cylinder was mounted in the JAS. The specimens were kept permanently moist with physiological saline solution.

Definitions. Joint stability was defined as the PEFR possible until a torque of 1.75 Nm was reached. This torque was sufficiently low not to damage the soft tissue constraints yet high enough to demonstrate laxity. In a pilot study using two specimens, five repeated measurements until the torque limit of 1.75 Nm, showed no increase in PEFR angle due to lesions of the capsule during the previous tests. Joint compression forces (axial force along the forearm and a joint compression force perpendicular to the forearm) were applied to simulate the in vivo situation, and the specimens were tested in different flexion angles to evaluate a possible difference in ligamentous function.

Experimental protocol. Variable factors were joint flexion (0, 30, 45 and 90°) and the six cutting sequences of ligaments and capsule with three specimens in each, as shown in Fig. 3. The incisions of the Lateral Collateral Ligament Complex (LCLC) were divided into an anterior part anterior to the longitudinal radial axis, and a posterior part posterior to the axis (Fig. 3). Constant factors during all tests were the maximal supinated position of the forearm, a forearm axial force of 15 N (along the X axis), and a joint compression force of 5 N perpendicular to the forearm thereby acting vertically downwards (along the Y axis). The Z force was automatically kept within 0± 0.25 N during all tests. The maximal joint congruence in each position was defined as the start position. This was reached by manually moving the joint along the X- and Z-axes and in rotation until the deepest joint position on the Y- and X-axes was measured.

Dislocation model. During each test, the constant forces to the joint were applied as the first step. Then, PEFR was performed stepwise (0.037°/step), and for each step simultaneous data

1	Ant cap	Post cap	pLCLC	aLCLC	MCLC
2	Post cap	Ant cap	pLCLC	aLCLC	MCLC
3	Ant cap	Post cap	MCLC	pLCLC	aLCLC
4	Post cap	Ant cap	MCLC	aLCLC	pLCLC
5	aLCLC	pLCLC	Ant cap	Post cap	
6	pLCLC	aLCLC	Post cap	Ant cap	

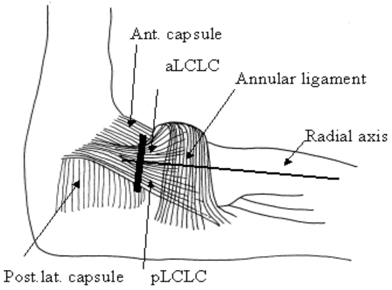

Figure 3

The six test sequences (1-6 in the table) with 3 specimens in each group, and illustration of lateral ligament section (line). Anterior LCLC + posterior LCLC = lateral collateral ligament complex = (LCLC), and MCLC is medial collateral ligament complex (not shown).

of both position and force from the three axes and from the rotation were collected. Each test was terminated automatically when rotational torque reached 1.75 Nm. When only the Medial Collateral Ligament Complex (MCLC) was intact or when no ligaments or the capsule were intact, the tests were terminated manually, since the PEFR torque limit was never reached in these situations, and the PEFR continued even though the posterior dislocation had occurred.

Data analysis.

The maximal PEFR angle reached at the 1.75 Nm torque limit was extracted from all log files as the measure of stability. Paired t-tests in SPSS® software were used to describe differences after change of flexion angle or after ligament division. P-values less than 0.05 were considered significant. The cutting sequences allowed 6 to 18 specimens to be tested in each of the test situations. From earlier tests and pilot testing we have a standard deviation of measurements on the intact joints of 2 degrees, and a standard deviation of differences of 0.5 degrees. Power analysis (SPSS®) of test situations with 6 specimens showed that a mean difference in PEFR of 0.7 ± 0.5 (mean ± 95% conf.int) degrees would be detectable with a power of 0.79 when using these parameters.

Results

The mean maximal PEFR in the intact joints increased 83% (range 65-110%) from 3.3° ± 0.87° (mean ± 95% conf.int) in the extended position to 6.0° ± 1.38° in 30° flexion ($p<0.01$), while further flexion only increased the maximal PEFR to 7.1° ± 1.41° in 90° flexion (n.s.), Fig. 4.

Fig. 5 illustrates PEFR with the capsule *or* the LCLC incised relative to the intact joint (as a ratio). In the extended position just a small increase of maximal PEFR is seen when only

one of the structures is incised (LCLC 35% ± 39% (mean ± 95% conf.int): p=0.07, capsule 48% ± 22%: p=0.01), whereas in the flexed positions a larger change is seen when the LCLC is cut (i.e. at 30° 133% ± 76%: p=0.04), but just a minor change is noted when only the capsule is sacrificed (10% ± 13%: p=0.13). When both the LCLC and the anterior capsule were incised, all ligamentous constraint to PEFR was absent and the preset torque limit was never reached as the PEFR continued. Therefore the tests in this situation were terminated
manually.

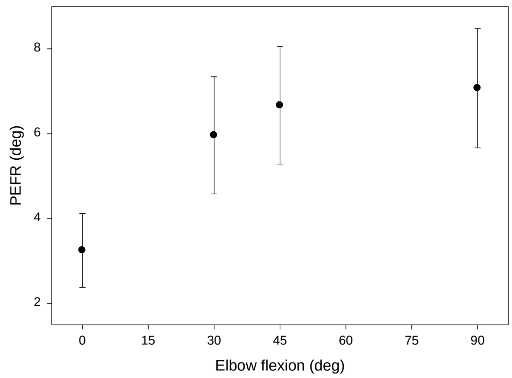

Figure 4

PEFR (degrees) until an applied torque of 1.75 Nm in the intact joint versus joint flexion angle (degrees). Mean and 95% confidence intervals are given.

None of the 12 specimens tested with only the MCLC intact completed the posterior dislocation because in all cases the coronoid process remained anterior to the trochlea. Only with the MCLC incised did a complete posterior dislocation occur.

No difference in maximal PEFR was found after separate incision of the anterior or the posterior part of the lateral collateral ligament complex. The entire width of this ligament complex had to be incised before any laxity occurred in addition to the inherent laxity.

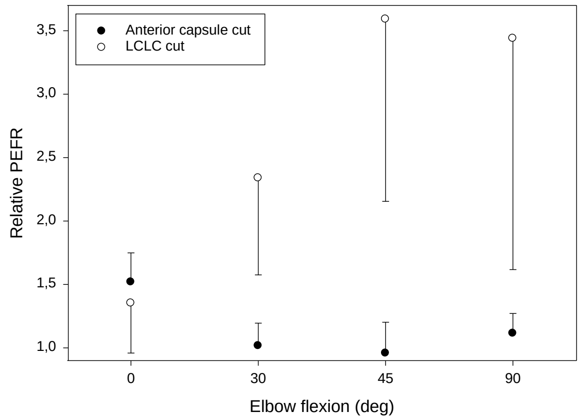

Figure 5

PEFR until a torque of 1.75 Nm after incision of the anterior joint capsule or the LCLC versus joint flexion (degrees). The PEFR is indicated as a relative measure compared with the intact joint at the same flexion angle. Mean and 95% confidence intervals are shown.

As the posterior capsule had only a negligible effect in relation to the PEFR after radiohumeral dislocation when both the LCLC and the anterior capsule were incised, it is not described in detail.

Discussion

Our experimental model is designed to perform the posterior elbow joint dislocation as a pathological external forearm rotation (PEFR) leading to ulno-humeral dislocation, as this in previous studies is considered to be a possible mechanism of the posterior dislocation (Osborne and Cotterill, 1966)(Kinast et al 1986)(O'Driscoll et al 1991). Previous experimental studies did not allow control of both compression forces and rotational torque in order to simulate the *in vivo* situation.

Previous authors have described and emphasized the importance of the LCLC as a stabilizing component of the joint (O'Driscoll et al, 1991)(Nestor, O'Driscoll and Morrey, 1992)(Cohen and Hastings, 1997), and some of these described the lateral ulnar collateral ligament (LUCL) as a separate component of the LCLC.(Morrey and An, 1985) In the present study we tested the anterior and the posterior part of the LCLC individually, the anterior capsule and the MCL as restraints to PEFR and ultimately to the posterior dislocation when it is performed experimentally according to the mechanism described above.

The experimental results underlines that rupture of the LCLC is the requisite lesion for PEFR to occur, and it demonstrated the anterior capsule to be a stabilizer against PEFR in the extended joint position. Slackening of the anterior capsule in the intact flexed elbow resulted in doubling of the PEFR compared with the extended elbow (Fig 3). Morrey and An(1983) found the anterior capsule to provide up to 40% of the resistance to valgus-varus loading and 85% to distraction with the elbow in extension, and Tyrdal and Olsen(1998) found valgus-varus laxity during flexion of less than 60° in joints with anterior capsule damage after a hyperextension trauma. A study performed by Nielsen and Olsen (1999) with another experimental set up, did not find any stabilizing effect of the anterior capsule in relation to valgus-varus stability. This does not contradict the data from Morrey and An (1983), however, as the collateral ligaments remained intact during the tests of the joint kinematics and the joints were not examined in full extension.(Nielsen and Olsen, 1999) Thus, all findings correlate well, and indicate an important role of the anterior capsule as a primary stabiliser in the fully extended elbow, and as a secondary stabiliser to PEFR in all other joint positions.

O'Driscoll et al.(1992) introduced a "circle concept" for posterior dislocation which describes progressive capsuloligamentous disruption in three stages, starting laterally and continuing both anteriorly and posteriorly towards the medial side of the joint, but sparing the anterior medial collateral ligament (AMCL) from disruption. We agree with the concept as far as the LCLC and the capsule are concerned, but in our experimental set up which included constant joint compression forces, the dislocation was not complete until the MCLC was severed.

Morrey and An (1985) introduced the term Lateral Ulnar Collateral Ligament (LUCL) for the posterior part of the Lateral Collateral Ligament (LCL). O'Driscoll et al (1991) and other authors (Morrey and An, 1983) believed this ligament to be the prime ligamentous stabiliser to PEFR, and that restoration of the LUCL part of the lateral collateral ligament complex to be the operation of choice for PLRI or recurrent elbow dislocations.(Nestor et al, 1992) Other authors recommended a repair of the entire LCL.(Osborne and Cotterill, 1966)(Hassmann, Brunn and Neer, 1975)(Durig, Muller, Ruedi and Gauer, 1979)(Nestor et al, 1992)(Olsen, Væsel, Sojbjerg, Helmig and Sneppen, 1996)(Cohen and Hastings, 1997) We chose to divide the LCLC into an anterior and a posterior part relative to the radial axis, as we were not able to define the LUCL and LCL separately in our specimens. We were not able to detect any functional difference between the anterior and the posterior part of the ligament complex in relation to PEFR, as both had to be incised before any increased PEFR could be observed. Therefore we see the lateral collateral ligament complex as one structure functionally, and our study does not justify the subdivision of the ligament. Similarly Olsen et al. (1996 and 1998) reported the LCLC to be a complex structure and they were unable to identify discrete bands anatomically or functionally. Also Imatani et al. (Imatani, Ogura, Morito, Hashizume and Inoue, 1999) and Cohen and Hastings (1997) believe the LUCL contributes to rather than is a major constraint to PLRI, the first authors having difficulties in defining the LUCL by microscopy.

Previous authors have reported LCLC rupture in clinical investigation of posterolateral rotatory instability (PLRI) (Morrey and An, 1983)(O'Driscoll et al, 1991)(Nestor et al, 1992)(Cohen and Hastings, 1997), and complete rupture of both collateral ligament complexes and also extensive damage in the anterior capsule were found in all subjects in a perioperative study of patients following posterior dislocation.(Josefsson et al, 1987) Concurringly, all these structures had to be incised before occurrence of complete dislocation in our study. The present study does not focus on the annular ligament because Josefsson et al (1987) found it to remain intact in all cases following posterior elbow dislocation.

The significance of removing the muscle tissue in the experimental set up is not fully known. However, it is agreed that muscle forces tend to stabilise the joint in one study where muscle forces were applied through weights connected to the tendons in order to simulate the *in vivo* situation.(O'Driscoll et al, 1992) Cohen and Hastings (1997) report an isolated stabilising effect of the common extensor muscle insertion against posterolateral elbow instability in another experimental study. We know from a previous study of the bony constraint of the elbow joint, that increased axial joint compression force has a stabilising effect against PEFR (Deutch et al 2002). Therefore, the absent muscular contraction in cadaver studies probably tends to overestimate the effects of ligamentous insufficiency in relation to an *in vivo* instability.

In conclusion, the LCLC a the primary ligamentous restraint to PEFR which may ultimately lead to dislocation of the elbow, whereas the anterior capsule is a secondary stabiliser. Only in the extended joint is the anterior capsule a primary and the LCLC a secondary stabiliser. The MCLC is not a restraint to PEFR, but the MCLC had to be sacrificed with all other ligaments and the entire capsule before a complete experimental elbow joint dislocation occurred. Therefore the MCL is a tertiary stabiliser to PEFR and possible posterior elbow dislocation. The LCLC appears to be one functional unit, as we found no separate stabilizing function of either LUCL or LCL.

Perspectives

This study relates to the mechanism of posterior elbow joint dislocation. A previous experimental study from our laboratory found the osseous elbow joint specimen to be most susceptible to PEFR, and thereby probably to dislocation, during varus stress and elbow flexion of 10° to 30°.(Deutch et al, 2002) Other studies showed the LCLC to be an important stabilizer to varus stress (Olsen, Søjbjerg, Dalstra and Sneppen, 1996)(Olsen et al, 1998), and our present study indicates the LCLC to be the prime soft tissue constraint to PEFR in elbow flexion. These observations enhance the principal stabilizing role of the LCLC in relation to PEFR and dislocation.

In vivo, our data indicate that during a sufficient axial force along the forearm, as in a fall on the outstretched hand, an external rotatory torque, combined with varus stress and the elbow in approximately 30° of flexion, may be the optimal conditions to start the sequential disruption of ligaments and capsule leading to an elbow joint dislocation.

During operative procedures on the elbow, either the posterior or the anterior part of the lateral collateral ligament can be transected without inducing posterolateral rotatory instability of the elbow.

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Manuscript III

Elbow joint stability following experimental osteoligamentous injury and reconstruction

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Abstract

Elbow joint dislocation was simulated on cadaver specimens in order to quantify laxity induced by radial head and coronoid process lesions, either alone or in combination with collateral ligament insufficiency. Also effects of lateral ligament reconstruction and radial head prosthesis replacement were considered.

Absence of the radial head and the coronoid process induced rotatory laxity of 145% and 128% (both p<0.01) compared with the intact joint. When both were absent, the joints subluxated regardless of collateral ligament status. Isolated radial head prosthesis implantation prevented this subluxation and laxity almost normalized. Lateral collateral ligament reconstruction prevented major laxity even in the absence of the radial head. Lateral collateral ligament reconstruction and radial head prosthetic replacement yielded restraint against gross instability in the maximal instable situation ("terrible triad"). The lateral collateral ligament is the prime stabilizer to external rotation, and reconstruction of this alone, even with and absent radial head is beneficial.

Introduction

Despite difficulties in treating of combined osseous and ligamentous injury in the elbow, only limited data address this matter in the literature. Instability following these complex injuries is focused upon in some clinical studies,[3,8,14,19,22,28,41,42,49] whereas most experimental studies describe the laxity following either ligamentous[2,5,9,11,13,15,16,24,25,29,32-36,39,43,45,46,48] or osseous injuries.[1,18,20,21,31,38] Only two previous experimental studies address a combination of injuries.[27,44] Sojbjerg et al[44] investigated the elbow joint laxity to valgus-varus and internal-external rotatory stress after stepwise transection of the annular ligament (AL), radial head (RH), and lateral collateral ligament (LCL). They concluded that the AL was the prime stabilizer of the lateral aspect of the elbow, the LCL having only a minor stabilizing function. Furthermore, they reported that isolated excision of the RH caused slight varus and external rotatory laxity. Morrey et al[27] defined the medial collateral ligament (MCL) as the primary constraint to valgus stress and the RH as the secondary constraint, and that isolated absence of the RH did not alter the motion characteristics of the elbow in the case of intact ligaments. Thus, it appears that the specific roles of the component structures contributing to stability of the elbow have not been fully determined.

Especially the "terrible triad" of the elbow (medial and lateral collateral insufficiency complicated with RH fracture and coronoid process (CP) fracture)[15] seems prone to acute or recurrent dislocations.[19] To our knowledge, the "terrible triad" has never been investigated experimentally with regard to laxity resulting from insufficiency of the involved structures.

Forced external rotation of the forearm relative to the humerus, which "unlocks" the inherent osseous stability of the elbow joint, is considered to be the initial step for posterior elbow dislocation to occur.[32] This rotation has been defined as pathological external forearm rotation (PEFR)[7], and it is the essential mechanism of clinical posterolateral rotatory elbow instability (PLRI).[30] We developed an experimental model of elbow joint instability that allows evaluation of PEFR following excision of the various constraints of the elbow joint.[7,17]

The aim of the present experimental study was to evaluate how fractures – alone and in combination with clinically relevant ligamentous injuries – affect the elbow joint resistance to PEFR and ultimately to posterior dislocation. Furthermore, we examined the degree to which clinically employed reconstructive procedures re-establish stability in the joint.

Materials and methods

Specimens

The experiments involved 12 fresh frozen upper extremities (nine left and 3 right) obtained from 9 females and 3 males with a median age of 75 years (range 65-89). All specimens were resected through the mid-humeral and carpal levels. Soft tissues including the joint capsule were removed, leaving the interosseous membrane and ligaments intact (lateral collateral ligament, annular ligament and medial collateral ligament). Specimens were examined prior to inclusion and subsequent to the tests. None of the specimens had signs of joint pathology (e.g. arthritis or fracture).

Joint Analysis System

The Joint Analysis System (JAS) is a custom-made linear motion system working in the three dimensions of a coordinate system (X, Y and Z), with the additional possibility of rotational movement about an axis (R) lying in the X-Z-plane (Fig 1). [7,17] Each of four stepping motors including switch units (Berger-Lahr®, Germany), provides one of the four movements possible. Linear movements occur in steps of 5 μm and rotation in steps of 0.037°. Strain gauges, calibrated with weights prior to specimen mounting, measure the forces acting along the X-, Y-, and Z-axes, as well as the torque generated about the R-axis. A personal computer equipped with LabVIEW® 5.1 (National Instruments®, Austin, Texas) controls the stepping motors and continuously logs data sets about position and force/torque for all axes.

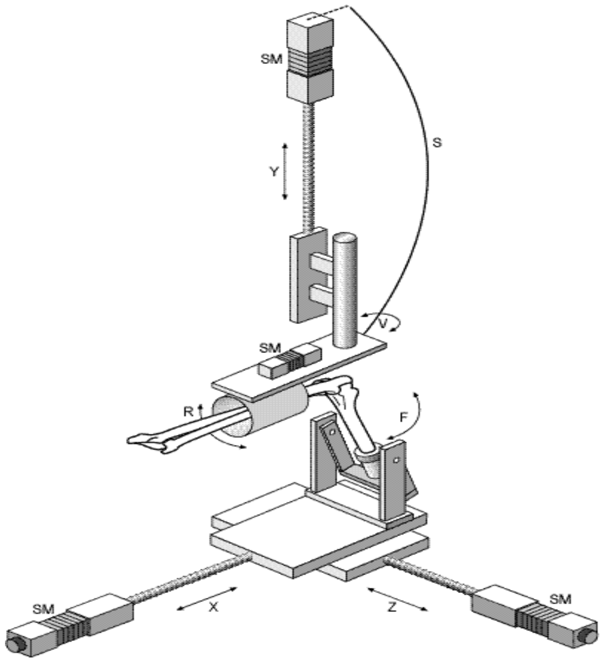

Figure 1

The Joint Analysis System (JAS) with a specimen mounted. The axes of linear movement are marked X, Y and Z, and rotation about the forearm (PEFR) is marked R. These movements are controlled by stepping motors (SM). F denotes elbow flexion, which is preset, and V is the free horizontal (valgus-varus) movement.

Specimen fixation.

The humeral fixture is mounted on the X- and Z-axes motion systems so that combined activation of these can move the humerus in any direction in the X-Z-plane (Fig 1). The axis of elbow flexion defined by the concentric arcs formed by the capitellum and the trochlea, parallels the Z-axis, and tilting the humerus in its fixture sets the degree of elbow flexion (F). The forearm is positioned in maximal supination centrally in a cylinder and secured with multiple screws from different directions against the bones. Alignment of the forearm with an axis through the proximal radioulnar joint and the distal ulna lying in the centre of this cylinder ensures that axial force from the forearm is transmitted to the humerus almost equally through the radius and ulna.[12] The cylinder is attached to the R-axis stepping motor through a wire system, providing external rotation of the forearm *en bloc* in relation to the remaining system and thereby the humerus. The forearm fixation system can rotate freely about an axis parallel to the Y-axis, allowing unconstrained valgus or varus displacement of the forearm during testing.

Experimental model

For each position of joint flexion, the position of highest congruency between the articular surfaces of the forearm and the humerus was defined as the natural joint position from where each test was started. This position established by applying constant joint compression forces along the X- and Y-axes and activating all motion systems sequentially by an iterative process until the deepest joint positions on the Y- and X-axes were obtained. The actual tests started with application of the constant forces, followed by external rotation of the forearm until a predefined torque level. Hence, if the restraints to axial shortening were insufficient to overcome the constant axial force, the joint would (sub-)luxate after application of constant forces. The speed for all movements was set at 80 steps/s.

Stability to forced external rotation of the forearm was measured as that rotation possible until a torque of 1.75 Nm attained. In previous studies, this torque has proven sufficiently low as to cause no damage to the soft tissue constraints, yet high enough to demonstrate instability. When this torque level could not be reached due to massive loss of rotatory constraint, PEFR could not be quantified and the condition was defined as maximal instability.

Experimental protocol

The specimens were divided in four groups with different sequences of ligament and osseous injuries and reconstruction (Table 1). At each injury level, the joint was tested at four degrees of elbow flexion (0, 30, 45 and 90°). Constant factors during all tests were maximum forearm supination, an axial forearm force of 15 N along the X-axis, and a joint compression force of 5 N along the Y-axis. The Z-force was automatically kept within 0 ± 0.25 N during all tests.

1	(n=4)	Intact	RH-exc	LCL-recon	MCL-inc		
2	(n=4)	Intact	CF st2	RH-exc	MCL-inc		
3	(n=2)	Intact	CF st2	RH-exc	RH-prost	MCL-inc	LCL-recon
4	(n=2)	Intact	RH-exc	CF st2	RH-prost	MCL-inc	LCL-recon

Table 1.

The four test sequences. The intact joints were initially tested, after which the joints were again tested following fracture with or without adjacent severance/reconstruction of ligamentous structures. (Cf st2 = coronoid fracture stage 2.)

The radial head was excised without disrupting the annular ligament by retracting the anterior part of the annular ligament distally. A modular radial head prosthesis was used (Evolve®, Wright Medical Technology Inc., Arlington, TN) in order to match the diameter and height of the excised radial heads as closely as possible. In order to spare the soft tissue constraints, the prosthesis was implanted after an osteotomy of the lateral condyle, the latter subsequently being refixated in the anatomic position with cancellous screws (Fig 2).

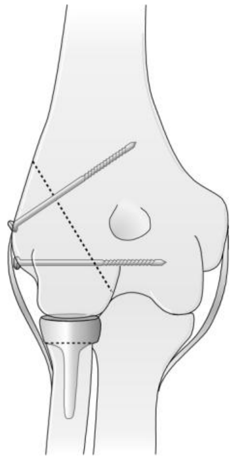

Figure 2

Lateral osteotomy performed prior to implantation of the radial head prosthesis in order to spare lateral soft tissues. Refixated with screws.

The coronoid fracture was a Stage II according to the Regan and Morrey classification,[38] in which the height of the coronoid is reduced by 50%. A pilot study also considered two specimens with a Stage I CP fracture (tip of CP).

The lateral collateral ligament was reconstructed according to the method described by Morrey et al[26] with a 10 mm mid-triceps graft. With the joint positioned in 90 degrees of flexion, boreholes and heavy sutures in the supinator crest and in the isometric point of the lateral epicondyle fixed the graft after a tension with 5 Newton was applied. As an earlier study had demonstrated, that gross laxity would occur without reconstruction of LCL, this situation was not tested.[6] The same study also revealed, that the MCL is not a restraint to PEFR in joints without fracture, but that might change after a fracture. Therefore, MCL incision after fracture was included in the present study.

Data analysis

The PEFR angle reached at the 1.75 Nm torque limit was extracted from all log files as the measurement of stability. Paired t-tests or t-tests in SPSS® software were used to analyse differences after injuries or repair. P-values less than 0.05 were considered significant.

Results

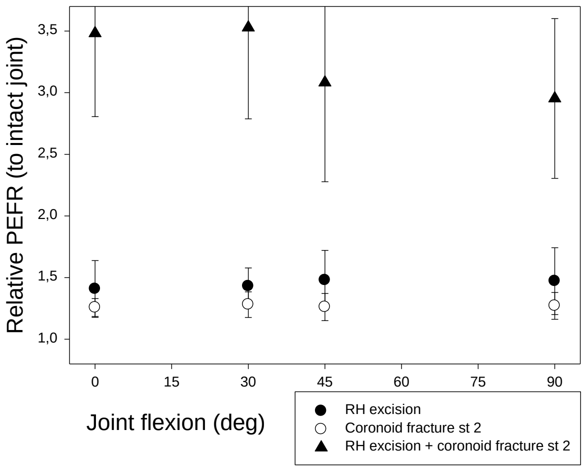

Figure 3

Relative change of PEFR (Y-axis) after RH-excision, coronoid fractue Stage II, or both in different flexion positions (X-axis). PEFR relative to the intact stage. Error bars indicate 95% confidence intervals.

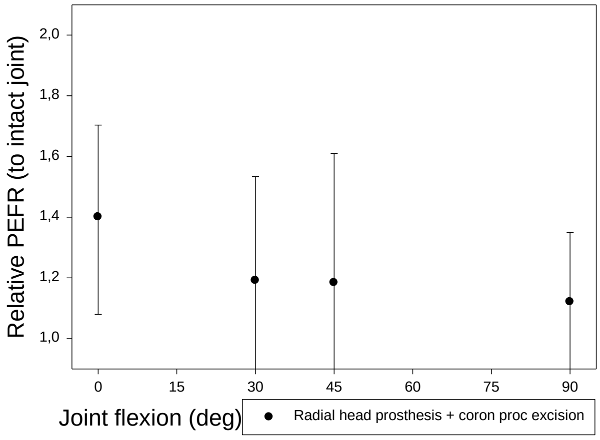

Figure 4

Relative change of PEFR (Y-axis) after RH-prosthesis and coronoid fracture stage 2 in different flexion positions (X-axis). Relative PEFR as compared with the intact stage. Error bars indicate 95% confidence intervals.

Excision of the RH and the CP both resulted in significant PEFR increase (mean values: RH 45% and CP 28%, both $p<0.001$), but no difference in PEFR increase was found between the fractures ($p>0.1$) (Fig 3). After isolated Stage I CP fracture on two specimens (pilot study) no increase in PEFR was seen (1 and 3% respectively, $p>0.1$). Combined lesion of the RH and the CP (Stage II) resulted in immediate ulnohumeral subluxation after application of the axial force as the forearm migrated proximally until the radial neck met the capitellum. In this situation the PEFR increased more than 300% ($p<0.001$) (Fig 3). The subluxation was prevented after implantation of the RH prosthesis, and except for the extended joint position, the PEFR decreased towards the value of the intact joint (PEFR=117%, p>0.1) (Fig 4). Subsequent severance of the MCL resulted in an insignificant PEFR increase (8%, p>0.1).

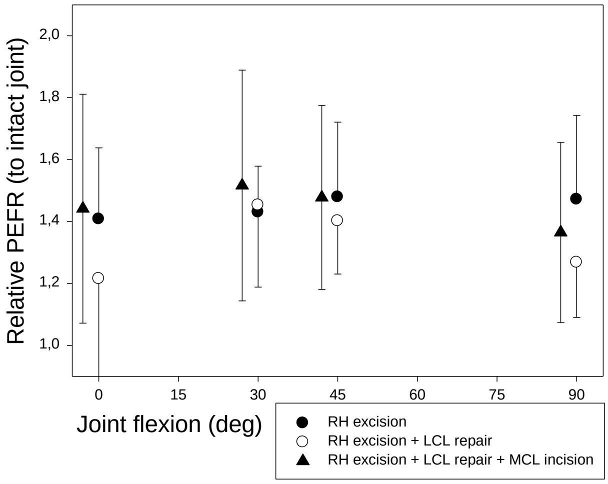

Figure 5

Relative change of PEFR (Y-axis) after RH-excision, RH-excision + LCL-reconstruction, and RH-excision + LCL-reconstruction + MCL-incision in different flexion positions (X-axis). PEFR relative to the intact stage. Error bars indicate 95% confidence intervals.

Figure 5 illustrates differences in PEFR following RH excision, RH excision + LCL reconstruction, and the same including MCL incision. A non-significant decrease in PEFR is seen following LCL incision and subsequent reconstruction in the joints with the RH excised (9%, p>0.1). Subsequent MCL incision in this situation resulted in an insignificant PEFR increase (7%, p>0.1).

Finally, after implantation of RH prosthesis and a LCL reconstruction as a minimum operation of the "terrible triad" (Fig 6), the resulting PEFR was 168% of the intact joint (p<0.001) but subluxation and gross laxity were prevented.

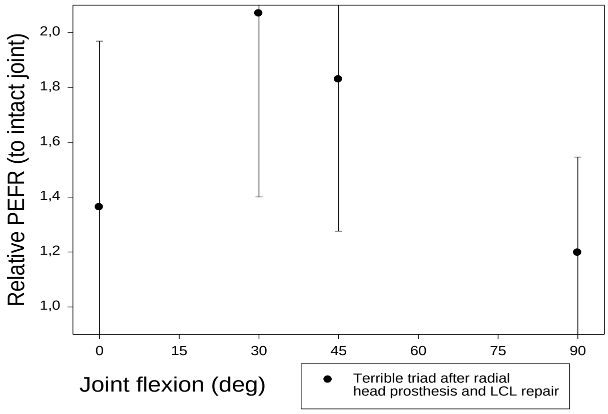

Figure 6

Relative change of PEFR (Y-axis) after RH-prosthesis and LCL-reconstruction of the "terrible triad" in different flexion positions (X-axis). PEFR relative to the intact stage. Error bars indicate 95% confidence intervals.

Discussion

Elbow joint constraint to posterior dislocation has not previously been investigated experimentally following combined lesions of bone and ligaments. The present study examines the constraint in relation to the most common fractures seen clinically after a joint dislocation (RH and CP)[23,28,42,49] with or without adjacent ligamentous damages to the collateral ligaments.

In the present study, isolated RH excision increased the PEFR by 45% (Fig 3). In a study not incorporating joint compression force, Jensen et al[18] similarly observed increased joint laxity in relation to external rotation after RH excision, and proposed a slackening of the LCLC as the mechanism responsible. During our experiments, we also noticed slackening of the LCLC after RH excision. Therefore the RH may maintain rotatory constraint by a tensioning of the LCLC. In contrast, Morrey et al[27] reported that the RH could be resected without altering joint stability, but these authors did not investigate stability to forced external rotation.

The coronoid fracture Stage II played an independent role as constraint to PEFR in our study. A previous study concludes that elbows with a fracture greater than 50% of the coronoid height more readily displace when an axial load is applied.[4] Both studies indicate that a Stage II coronoid fracture (or worse) induces both axial and rotational instability in the joint. This correlates with findings in a clinical follow-up study, where recurrent dislocations related to coronoid fractures[19]. A recent study advises operative reconstruction of even small coronoid fractures, as this is considered to be an important restraint to redislocation.[47] Our pilot study did not reveal PEFR increase after a Stage I fracture, but our main study supports the suggestion that a Stage II fracture in an instable elbow should be reconstructed, if possible.

Combined CP fracture and RH excision increased laxity dramatically. However, RH prosthetic replacement improved laxity in two ways. Firstly, the joints no longer subluxated as the prosthesis kept the forearm from translating posteriorly in relation to the distal humerus because the prosthesis restored the radio-capitellar contact. Secondly, the dramatic increase in PEFR induced by the two fractures almost normalised (Fig. 4). Although such combined fractures without ligamentous damage would seem most unlikely *in vivo*, the experiment highlights the specific effects of the two fractures and as well as the prosthetic replacement in relation to PEFR and posterior elbow dislocation.

We combined experimental fractures with ligamentous injuries in order to mimic clinical situations. One combination corresponds to the clinical situation following dislocation of the elbow with rupture of all ligaments and loss of RH support due to comminuted fracture, but with an intact CP. The insignificant changes in PEFR (Fig 5) indicate that the method of LCL reconstruction reported by Morrey et al.[26] provides a good restraint to PEFR, even with an excised RH and a damaged MCL. Several authors have suggested use of RH prosthetic replacement.[10,14,20,37] The present study indicates that by use of a LCLC plasty, gross instability may be avoided even without implantation of a RH prosthesis.

Severance of the MCL following either the double fracture, the LCL reconstruction, or the RH prosthesis resulted in a slight (but in our study insignificant) increase in PEFR. After this MCL incision, we noticed an increased carrying angle (valgus displacement) in the starting position before each test. This concurs with a previous study emphasising the importance of the MCL in elbows with valgus instability.[27]

RH prosthesis and reconstruction of the LCL is reported as a “minimum procedure” regarding “the terrible triad”[40], and in our set-up this procedure resulted in a mean PEFR of 168% of the intact situation (Fig. 6). However, the most important feature was that specimens were now resistant to both subluxation and dislocation, even though both the CP and the MCL were damaged.

In conclusion we found that both the RH and the CP acted as independent restraints in relation to posterior dislocation in our experimental set-up. When both were excised (the coronoid as a Stage II[38]) the joint subluxated by axial force regardless of intact collateral ligaments. This subluxation could be prevented by insertion of a RH prosthesis, and the laxity to PEFR almost normalized. Isolated LCL-reconstruction seemed a sufficient constraint to forced external rotation following damage to both collateral ligaments and RH insuffiency. The “minimum procedure” (LCL-reconstruction and RH prosthesis)[40] of the “terrible triad”[15] appeared to provide sufficient restraint against gross posterolateral elbow joint laxity and redislocation.

Acknowledgement

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