Journal of Biomechanics 46 (2013) 677–682

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Utility of an image-based technique to detect changes in joint congruency following simulated joint injury and repair: An *in vitro* study of the elbow

E.A. Lalone [a,d,e], J.W. Giles [a,e], B. Alolabi [b,e], T.M. Peters [a,d], J.A. Johnson [a,c,e], G.J.W. King [a,b,e,*]

[a] *Biomedical Engineering, The University of Western Ontario, London, Canada*
[b] *Department of Surgery, The University of Western Ontario, London, Canada*
[c] *Department of Mechanical and Materials Engineering, The University of Western Ontario, London, Canada*
[d] *Robarts Research Institute, The University of Western Ontario, London, Canada*
[e] *Hand and Upper Limb Centre, St. Joseph's Hospital, London, Canada*

ARTICLE INFO

Article history:
Accepted 24 November 2012

Keywords:
Collateral ligament
Elbow
Joint congruency
Post-traumatic arthritis
Joint kinematics

ABSTRACT

Background: Investigating joint mechanics is important when determining the etiology of osteoarthritis, as degenerative changes are thought to occur due to altered joint mechanics. The objective of this study was to demonstrate the utility of an x-ray computed tomography-based approach to evaluate joint congruency in the setting of subtle kinematic alterations, employing an *in vitro* model of collateral ligament repair of the elbow.
Methods: Active and passive elbow flexion was performed in 4 and 5 fresh-frozen cadaveric upper extremities respectively using an elbow motion simulator in the valgus gravity dependent positions. The collateral ligaments were sectioned and repaired. A registration and inter-bone distance algorithm were then used to examine ulnohumeral joint congruency (quantified as surface area) throughout elbow flexion. Valgus angulation was also measured.
Findings: Following ligament sectioning and repair, there was a $1.2 \pm 1.0^\circ$ increase in valgus angulation in active flexion and a $21.2 \pm 26.2\%$ decrease in surface area. In passive flexion, valgus angulation increased $3.3 \pm 2.2^\circ$ and surface area decreased $57.9 \pm 39.9\%$.
Interpretation: The technique described to quantify joint congruency proved to be sensitive enough to detect large changes in joint surface interactions inspite of only small changes in traditionally measured kinematics. These changes in joint congruency may, in part, explain the high incidence of arthritis that has been reported following ligament injuries of the elbow, even in the absence of clinically detectable instability. This technique, when adapted for *in vivo* use, will be a useful tool to evaluate joint function and the effectiveness of treatments non-invasively.

1. Introduction

Post-traumatic osteoarthritis (OA) occurs following joint injuries such as fractures and dislocations. The associated degenerative changes may occur due to chondral damage from the initial trauma, or articular incongruity present as a result of residual subclinical joint instability (McKee et al., 1998; Ring et al., 2002). The exact mechanism of this disease is unknown (Hunter et al., 2009, 2005). Changes in the overall alignment of the joint or joint congruency are thought to be an important cause of long term cartilage injury (Beveridge et al., 2011). The objective of this study was to evaluate the utility of a previously developed joint congruency technique *in vitro*. We chose an elbow ligament injury, repair and rehabilitation model to elucidate the relationship between ligament repair surgery and rehabilitation on subsequent joint congruency as it relates to the development of OA.

Dislocations of the elbow are common, most frequently occurring as a result of a fall or more severe impact. Disruption of the anterior and posterior capsules as well as the medial and lateral collateral ligaments (MCL and LCL) has been documented following dislocation (Eygendaal et al., 2000; Pollock et al., 2009; O'Driscoll et al., 1992; Josefsson et al., 1987). While residual clinical instability is uncommon, the ligament healing is often incomplete resulting in slightly increased elbow laxity (Eygendaal et al., 2000). Previous *in vitro* kinematic studies examining collateral ligament repair have reported restoration of elbow stability following surgical repair of the collateral ligaments (Pichora et al., 2007; Dunning et al., 2001b; Fraser et al., 2008; Armstrong et al., 2000). Despite these findings however, post-traumatic arthritis has been reported in up to 50% of patients following dislocations at long-term follow-up (Eygendaal et al., 2000; Josefsson et al., 1984).

---

[*] Correspondence to: Hand and Upper Limb Centre, St. Joseph's Health Centre, 268 Grosvenor Street, London, Ontario, Canada N6A4L6.
Tel.: +1 519 646 6000x65762; fax: +1 519 646 6049.
E-mail address: gking@uwo.ca (G.J.W. King).

0021-9290/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2012.11.047

The relationship between altered kinematics due to residual ligament insufficiency and joint congruency was examined in the elbow. The hypothesis was that while traditional techniques used to investigate elbow instability were able to detect gross changes in the motion pathways of the joint, they would not be sufficiently sensitive to detect more subtle changes within the joint, which may have long term implications with respect to the potential development of elbow arthritis. Additionally, the effect of muscle stabilizers was examined in both active and passive elbow flexion using kinematics to detect changes in the motion pathways, and joint congruency.

2. Methods

2.1. Specimen preparation and experimental protocol

Five fresh-frozen upper extremities, extending from the shoulder to the fingertips were employed in this study (76.6 ± 3.0 yrs, Male). A pre-testing x-ray computed tomography (CT) scan was acquired for each specimen and used to ensure each specimen had no existing joint pathologies (64-slice scanner, GE Discovery CT750 HD, Waukesha, WI). Approximately 1000 slices were acquired for each specimen with a 512×512 reconstruction matrix (292 mAs, 120 kVp). The voxel dimensions were approximately $0.621 \times 0.621 \times 0.625\ \text{mm}^3$. Following scanning, the specimen was sectioned mid-humerus and therefore contained the elbow, wrist and hand articulations.

Each specimen was thawed at room temperature for 20 h. The specimen was clamped into the mount of an elbow motion simulator (Ferreira et al., 2010). The tendons of the biceps brachii, brachialis and triceps were isolated and secured to sutures which were attached to stainless steel cables extending to separate servomotors. Similarly, the tendons of the brachioradialis, pronator teres, supinator, wrist flexors (flexor carpi radialis and flexor carpi ulnaris) and extensors (extensor carpi radialis brevis and extensor carpi ulnaris) were isolated, secured to sutures and connected to pneumatic actuators using stainless steel cables. All soft tissues remained intact throughout preparation and were kept hydrated using saline throughout testing. Two (3D) optical position sensors were attached to the base of the simulator adjacent to the mounted humerus as well as directly onto the ulna near the distal end of the bone (dorsal side) using a bone-fixated mounting pedestal.

The elbow motion simulator was positioned in the valgus gravity orientation, with the medial epicondyle of the elbow directed upward and the long axis of the humerus parallel to the ground. Ulnohumeral joint congruency was examined in this study. In this position, the radiohumeral joint acts as a bony stabilizer to resist valgus laxity, while the ulnohumeral joint tends to open. As such, the valgus gravity dependent position is a provocative model to examine the effect of ligament deficiency on ulnohumeral joint stability. Additionally, previous studies have investigated the role of forearm rotation on elbow joint stability and determined that supination stabilizes the MCL deficient elbow (Armstrong et al., 2000). As such, pronated elbow flexion, with the arm in the valgus orientation was employed as the most provocative to detect changes in joint biomechanics after simulated MCL injury and repair.

Active flexion was performed in four specimens. Tone loading of 10 N was applied to the wrist flexors and extensors to stabilize the wrist. Passive elbow flexion was achieved in five specimens by the experimenter (B.A.) guiding the forearm throughout the arc of flexion, while maintaining the forearm in pronation. The elbow was first tested in the intact scenario during pronated, active and passive elbow flexion. As a model of residual mild elbow instability, the effect of collateral ligament injury and repair (MCL/LCL) was investigated. The anterior bundle of the MCL was released from its humeral origin, and the LCL was released from the lateral epicondyle and then repaired using a transosseous suture repair technique described previously (Pichora et al., 2007; Fraser et al., 2008). Sutures (#2 Hi-Fi ultra-high-molecular-weight polyethylene, ConMed, Linvatec, Largo, FL) were secured to each collateral ligament using a locking Krackow technique and the remaining ends were passed through the diverging bone tunnels, tied through a loop and then attached to a pneumatic actuator to provide accurate tensioning of the ligament. For this study, both the MCL and LCL were tensioned to 20 N (with the arm in the dependent position and the elbow at 90° of flexion, neutral rotation) using the actuators and then attached to a clamp mounted to the base of the motion simulator. This magnitude of tension was selected based on the findings of previous studies (Pichora et al., 2007; Fraser et al., 2008). Active and passive elbow flexion was then repeated with the ligaments repaired.

Subsequent to testing, each specimen was denuded. Anatomical landmarks were digitized to create clinically relevant coordinate systems using a calibrated tracked stylus (Johnson et al., 2000). Additionally, four delrin spherical 19 mm fiducials were attached to the humerus and ulna in previously described configurations and digitized using a calibrated-cupped stylus to record the position of each fiducial marker with respect to the bone optical sensor (humerus and ulna separately) (Lalone et al., 2012b).

2.2. Kinematic data analysis

Motion of the ulna and stationary humerus was recorded using an optical tracking system throughout continuous elbow flexion (0–120°) (Optotrak Certus®, NDI, Waterloo, ON, Canada).

Valgus instability of a collateral ligament deficient elbow is maximal between 70° and 90° (Eygendaal et al., 2000), therefore kinematic motion of the ulna with respect to the humerus was examined by selecting frames of motion at 30°, 60° and 90°. Valgus angulation, which describes the angulation between the long axis of the humerus and that of the ulna, was measured for each angle of flexion and was used to describe the kinematic motion pathways of the elbow as it relates to valgus instability.

2.3. Landmark registration protocol

A second CT scan (post-testing) of the denuded humerus and ulna, with the fiducial markers attached, was acquired using the same scanning protocol as the pre-testing CT. The subchondral surface and cortex of the humerus and ulna from both pre-testing and post-testing CT scans were reconstructed using the Marching Cubes Algorithm within VTK (Visualization Toolkit, Kitware, Clifton Park, NY) (Schroeder et al., 1998). The accuracy of this reconstruction was measured previously and had 0.3 ± 0.15 mm magnitude of deviation between the reconstructed bone surface and a digitization of the actual bone (Lalone et al., 2012a). Before acquisition of this post-testing CT, the bones are denuded and disarticulated. Additionally, fiducial markers are drilled into the cortical and subchondral surface of each bone. Target fiducial makers are also attached to the articular surface of the humerus and ulna. Therefore, the 3D reconstruction obtained from this CT appears rough and has holes directly in the subchondral bone surface making these models not suitable to calculate inter-bone distance. Therefore the reconstructed humerus and ulna from the pre-testing scan and the segmented subchondral region of the humerus and ulna (used in the inter-bone distance algorithm) were registered to the post-testing CT (containing the fiducial markers used in the registration) using the Iterative Closest Point (ICP) surface-based registration algorithm with three coarse points chosen for initial course alignment (Besl and McKay, 1992). The accuracy of this step has been previously described and is less than 0.4 mm (Lalone et al., 2012a). Additionally, 3D models of each fiducial marker were reconstructed and sphere-fit.

Paired-point registration was employed to render the 3D models into their respective position based on the tracked data. This registration protocol employing homologous fiducial markers has been described previously (Lalone et al., 2012b). Using the relationship between the fiducial and the bone tracker, and the transformation matrices describing the position and orientation of each bone during elbow flexion, the position of each fiducial was determined with respect to the camera for each frame of motion. This registration described the relationship between the CT coordinate system (which the bone reconstructions were in) and the camera coordinate system. This was used to then render the bone reconstructions into the camera coordinate system for each frame of motion. The accuracy of the registration technique has been described previously by investigating target and fiducial registration error values ($\text{TRE} < 0.88$ mm, $\text{FRE} < 0.25$ mm) (Lalone et al., 2012b).

2.4. Determination of joint congruency

To investigate the relative inter-bone distance and therefore overall joint congruency, an inter-bone distance algorithm was employed (Lalone et al., 2012a). This algorithm uses points on the subchondral surfaces to find the minimum distance between the two opposing surfaces. Proximity maps are used to visually examine the relative inter-bone distances using color mapping. The inter-bone distance corresponds to the cartilage thickness on the humerus and ulna as well as any spacing between the articulating surfaces. In this study, a maximal inter-bone distance of 4 mm was used to identify 'regions of close proximity' and is shown as a maximum value on the color-map scale. This 4 mm magnitude is not to reflect solely the cartilage thickness (which is not homogeneous across the humerus or the ulna), but rather serves as a limit in the inter-bone distances and as a scale in the proximity maps. Within this 'region of close proximity (<4mm)', four 'levels of proximity' were also measured by finding the surface area on the subchondral bone that was less than 0.5 mm, less than 1.5 mm, less than 2.5 mm and less than 3.5 mm inter-bone distance. The surface area within each level of proximity was measured for the humeral and ulnar subchondral surface at 30°, 60° and 90° of flexion in the intact and ligament repaired scenario.

2.5. Statistical analysis

A repeated-measures analysis of variance test with a Bonferroni correction was used to detect statistical differences in the measured surface area for each level of proximity in the intact and ligament repaired scenario under both active and passive motions. Statistical significance was initially set at $p < 0.05$ and