Measuring Soft Tissue Contributions to Elbow Joint Motion and Virtual Ligament Modelling: An In-Vitro Study

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INTRODUCTION: Knowledge of ligamentous contributions to joint stability is essential to restore normal joint range of motion and functionality through reconstruction procedures. Although, there has been numerous studies on the pathomechanics of the elbow joint [1-3], there have been very few rigorous and systematic attempts to characterize the roles of soft tissues during clinically relevant motions [4]. Furthermore, the contributions of these tissues after major joint reconstruction surgeries such as total elbow arthroplasty (TEA) are difficult to include during conventional pre-clinical testing of implants. The aims of this study were to analyze the relative contributions of individual elbow ligaments to joint stability and laxity, and to determine if virtual ligaments tuned to match the behaviors of their physical counterparts can effectively restore normal joint biomechanics in vitro.

METHODS: Five fresh frozen cadaveric elbows (two left, three right) from three male subjects (average age 72) were used for this study. In-vitro simulations were performed using a VIVO six degree-of-freedom (6-DOF) joint motion simulator (AMTI, Watertown, MA) capable of virtually simulating the effects of soft tissue constraints (virtual ligaments). Specimens were aligned and mounted onto the simulator using specimen-specific 3D printed custom fixtures. Coordinates of the origins and insertions of medial and lateral ligamentous structures were measured, and were used to define corresponding virtual models in a matching computational model of each specimen in VIVOSim (AMTI, Watertown, MA). Each elbow underwent flexion-extension (15 to 105 degrees of flexion) with an 80N joint reaction force (JRF) applied along the long axis of the humerus to reduce the joint and simulate the resultant effects of the biceps, triceps and brachialis. This motion was repeated with 3 Nm valgus and varus moments applied; a loading protocol to simulate gravity varus/valgus loading which has been used in the literature [3]. These data sets established baseline normal kinematics for each specimen. Sequential release of soft tissue constraints were performed by removal of the joint capsule in the first phase of the simulation followed by release of the PMCL, the AMC, the LUCL and the RCL structures. The neutral, valgus and varus loading protocols described above were repeated at each stage of dissection in order to measure any changes in joint kinematics. Furthermore, a displacement-controlled flexion-extension of the joint was performed which guided the joint using the exact baseline kinematics recorded for the intact joint, and changes in the resulting joint reaction force (JRF) were measured. These measurements allowed us to determine the effects of soft tissue release on varus/valgus laxity (during force-controlled motions) and varus/valgus constraint (based on resultant VV moments during displacement-controlled motions).

Furthermore, repeating this protocol after each stage of dissection allowed us to measure the force contributions of each ligament throughout the motions simulated, from which we could contribute ligament force-length behaviors based on origin/insertion kinematics. A two-stage optimization procedure was performed for each set of ligament data. First, origin and insertion coordinates were tuned such that JRF changes (forces associated with each ligament) positively correlated with ligament elongation. Next, ligament properties (resting length and stiffness) were tuned such that their predicted force contributions matched those measured experimentally through changes in the JRF. Based on these data, virtual ligaments were defined within the control system of the VIVO, and joint motion analysis was repeated with these virtual ligamentous stabilizers in place to see if normal joint kinematics were restored.

RESULTS: Release of the PMCL did not cause any statistically significant differences in the generated VV moments. Complete removal of the medial soft tissue complex, however, resulted in significantly lower valgus moments. Releasing the LUCL did not have any statistically significant effects on the generated varus moment, but removal of the RCL left minimal VV restraint, provided by the articulations alone (Fig.1). Application of virtual ligaments restored the VV stability of the specimens over the range of flexion with no statistically significant differences compared to capsule-cut kinematics (Fig. 2); however, the joint tended to be rotated varus compared to the capsule-cut kinematics by an average of one degrees over the range of flexion. After removal of the joint capsule, the average valgus angle demonstrated a significant increase at 30 degrees of flexion while the varus angle experienced a slight increase at 60 degrees of flexion (Fig. 3). Removal of the PMCL significantly increased the VV laxity at 30 degrees of flexion. Release of the AMCL led to subluxation of the joint and gross instability under valgus loading, but did not demonstrate any significant effects on the varus laxity. On the lateral side, removal of the LUCL complex resulted in no statistically significant differences compared to the capsule-cut phase. All specimens experienced dislocation under VV moments after the RCL was removed. VV laxity of the specimens were restored after the virtual ligaments were applied to the joint (Fig. 3). No dislocation, instability or subluxation was observed for any of the specimens; however, varus laxity of the joints at 30 and 60 degrees of flexion and valgus laxity at 90 degrees of flexion were statistically greater than the corresponding angles for the capsule-cut phase.

DISCUSSION: As concluded by previous studies [1], our results demonstrate the importance of AMCL and RCL structures as primary stabilizers under valgus and varus loading respectively. Also, as shown in figure 1, removal of ligaments changes the neutral VV moment line by misbalancing the ligamentous structures around the joint. Measured VV laxity of the joint in response to external VV loading demonstrated the importance of the PMCL under varus loading; a new insight on the contribution of PMCL to joint stability that has been recently also studied by other groups [2]. Virtual ligaments demonstrate the ability to restore the VV stability of the joint in the absence of any soft tissues attached to the osseous structures. Although increased levels of VV laxity are observed for the joint with virtual ligaments compared to the intact joint, optimized ligaments are able to restore the stability of completely injured specimens with no signs of dislocation or gross instability. This suggests that optimized ligament properties were likely in agreement with those of their physical counterparts. This also means that in-vitro testing of biomedical devices for the elbow, such as TEA implants, can be enhanced by virtual inclusion of soft tissue stabilizers.

SIGNIFICANCE: This work demonstrates a new technique for measuring soft tissue contributions to normal elbow motions during a variety of clinically relevant motions, and demonstrates the effectiveness of "virtual" ligaments for in vitro testing of elbow joint biomechanics, with applications in pre-clinical assessment of elbow implants.

REFERENCES: [1] Morrey and An, Am. J. Sports Med. (1983), [2] Golan et al., J. Shoulder Elbow Surg. (2016), [3] Morrey et al., Clin. Orthop. Relat. Res. (1991), [4] Hibberd et al., J. Sports Med. (2015)

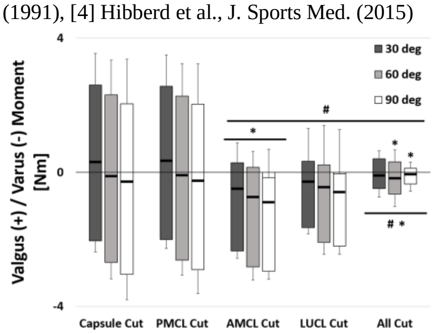

Figure 1: The generated VV moments by the joint due to removal of the ligaments (#p<0.05: Decrease over capsule-cut values, *p<0.05: Decrease over the previous level)

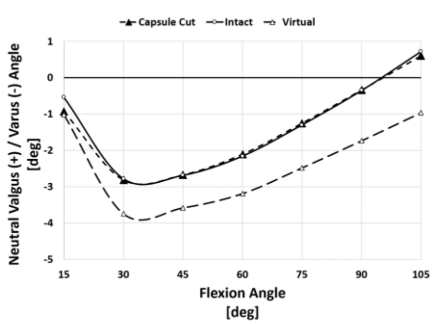

Figure 2: Virtual ligaments restore the neutral VV kinematics of specimens

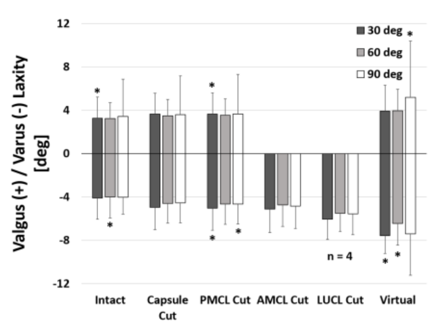

Figure 3: Average VV laxity of the specimens at different levels of ligamentous injury (*p<0.05: increase/decrease over capsule-cut values)