Journal of Hand Surgery Global Online 7 (2025) 146–151

Contents lists available at ScienceDirect

Journal of Hand Surgery Global Online

journal homepage: www.JHSGO.org

Original Research

The Effect of Arm Abduction and Forearm Muscle Activation on Kinematics During Elbow Flexion

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ARTICLE INFO

Article history:
Received for publication November 3, 2024
Accepted in revised form November 6, 2024
Available online December 11, 2024

Key words:
Elbow biomechanics
Elbow kinematics
Elbow valgus
Dynamic stabilizers

Purpose: As the elbow flexes with the arm at the side (0° humerothoracic abduction, HTA), it loses its valgus carrying angle. When the arm is abducted to 90° HTA, a varus torque tensions the lateral ligaments. Our purpose was to quantify the effect of abduction on elbow kinematics during active motion and the effect of lateral forearm muscle activation. We hypothesized that arm abduction would increase elbow varus angulation throughout flexion, and lateral forearm muscle activation would decrease varus angulation.
Methods: A dynamic elbow testing apparatus was employed in six human cadaver arms at two levels of arm abduction, 0° and 90° HTA. Six electromechanical actuators simulated muscle action, whereas joint position was measured to quantify the relationship between the forearm and humerus as the elbow was actively flexed.
Results: All elbows maintained greater varus angle with the arm at 90° HTA compared with 0° HTA, significant at 60° flexion, 4.3° versus 3.4°, 90° flexion, 8.0° versus 6.8°, and 120° flexion, 10.5° versus 8.9°. The abducted elbow demonstrated less varus angle when the lateral stabilizers were activated. A significant difference was found at 30° flexion, 0.9 versus 1.5, 60° flexion, 3.8 versus 4.3, and 90° flexion, 7.6 versus 8.0.
Conclusions: Elbow joint coronal plane kinematics were influenced by abduction of the arm to 90° HTA, and greater elbow varus angles were found throughout flexion when compared with the arm at side position (0° HTA). In addition, activation of lateral forearm muscles (90° HTA + Lat Stab) decreased elbow varus angulation throughout flexion.
Clinical relevance: Understanding the effect of varus torque on elbow biomechanics and the degree to which these effects are countered through dynamic stabilization may assist in arthroplasty and ligamentous reconstruction designs.

The elbow is tasked with positioning the hand in a stable manner relative to the trunk while allowing motion at varying arm positions. Elbow flexion and extension occurs about an axis of rotation, which is influenced by bony congruence, ligamentous restraint, and dynamic stabilization.[1–3]

Humeral-originating muscles create forces as great as a 16× weight in hand multiplier, resulting in a compressive force range of 350–2094 N across the elbow joint.[4–6] Compressive forces result in dynamic stability, which is substantial when the arm is at the patient's side, but less substantial when the arm is abducted away from the body. In arm abduction, elbow flexion and extension requires less force from the humeral-originating muscles (biceps, brachialis, and triceps), which lessens their contribution to dynamic stability (Fig. 1).[7,8] Forearm-originating muscles that originate from the lateral epicondyle (long wrist extensor and extensor carpi ulnaris) have demonstrated EMG activity that stabilizes the elbow experiencing a varus torque.[8] These forearm-originating muscles, however, produce less force than the biceps, brachialis, and triceps and cannot generate as much compression as the larger humerus originating muscles (Fig. 1).[7,9,10]

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https://doi.org/10.1016/j.jhsg.2024.11.006
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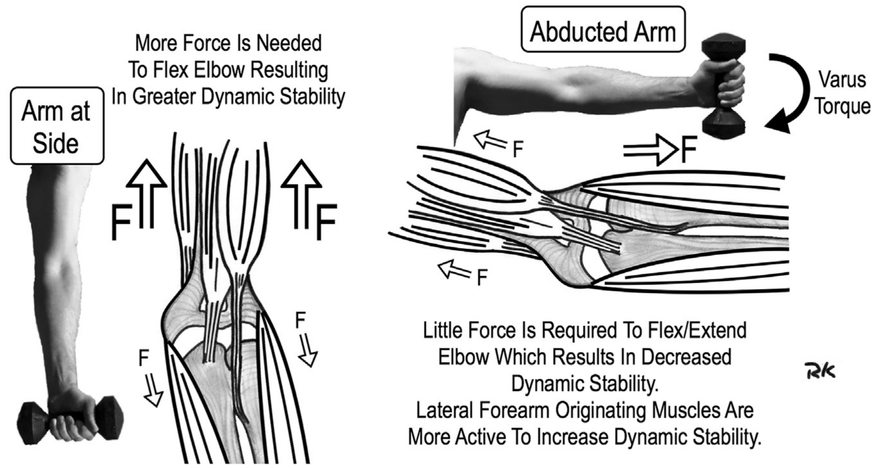

Figure 1. Arm abduction (90° HTA) imparts (1–25 Nm) varus torque. Dynamic stability is greater with the arm at the side. Arm abduction increases reliance on soft tissue stabilizers as dynamic stability decreases.

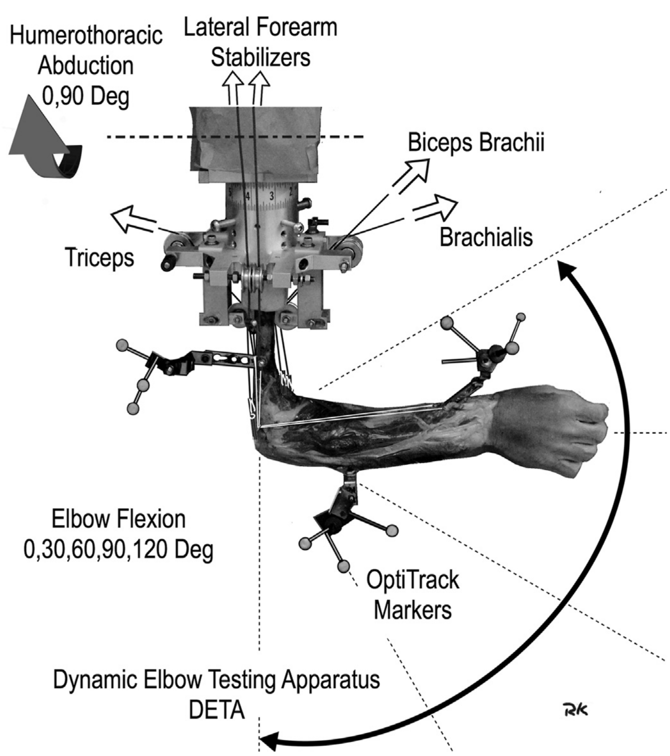

Figure 2. Dynamic elbow testing apparatus. The cadaver elbow is cycled through flexion in three conditions: at side position (0° HTA), 90° arm abduction (90° HTA), and ninety degrees arm abduction with lateral forearm stabilizers activated (90° HTA + Lat Stab).

Most activities of daily living require the arm to be abducted away from the body and exert a substantial torque on the elbow of up to 25 Nm.[8,11–13] These extrinsic forces place greater reliance on the soft tissue contribution for the maintenance of joint congruence, which is relied upon heavily not only after ligament reconstruction or repair but also in the native elbow when injury to the lateral ulnar collateral ligament leads to posterolateral elbow instability.[4,7,8,11,12] Consequences of varus loading patterns on mechanically linked total elbow arthroplasty designs can be seen in explanted polyethylene components that demonstrate burnishing, asymmetric thinning, delamination, and circumferential grooving consistent with edge loading.[13,14] These designs will often not repair the collateral ligaments and allow a majority of forces to be transferred to the hinge instead of through the native ligamentous support.[15,16]

A prior study in our laboratory used a dynamic elbow testing apparatus (DETA) to characterize elbow kinematics of the nonabducted arm, 0° humerothoracic abduction (HTA), which underwent a loss of valgus carrying angle throughout flexion, occurring primarily between 30° and 90° of flexion (Fig. 2).[17,18] The purpose of this manuscript was to use the same DETA to quantify elbow joint coronal plane kinematics when the arm is abducted (90° HTA). Additionally, we aimed to characterize the contribution of lateral forearm muscles in stabilizing the abducted arm.

We postulated that gravity would influence the abducted elbow and that we would record an increased varus angle throughout flexion. We postulated further that the dynamic stability afforded by the lateral forearm muscles would offset the increased varus angle encountered during arm abduction.

In this study we, therefore, measured the anatomic decrease in valgus angle by flexion angle when abducting the arm (90° HTA) and then, the effect of activating the lateral forearm muscles (90° HTA + Lat Stab) at 90° of arm abduction. The clinical significance of this research was to establish a baseline for elbow varus angle change when abducting the arm and for the contribution of lateral dynamic stabilizers, which will provide insight into arthroplasty and ligament reconstruction designs in the dependent and abducted arm positions.

Materials and Methods

Specimens

Five women and one man fresh frozen cadaveric right upper extremities, including the entire humerus, were prepared to be actuated within the experimental setup.

Testing apparatus

Six independently controlled electromechanical actuators (EMXG50188—BE233 Series Servomotors and Acroloop Controller Aries Series) applied forces to each muscle group crossing the elbow through a tendon suture-cable-clamp pulley system.[17,19] An optical tracking system was used to record elbow joint motion (Flex 13, OptiTrack, Northern Digital). An anatomical coordinate system was generated by digitizing anatomic landmarks.[20] Joint angle

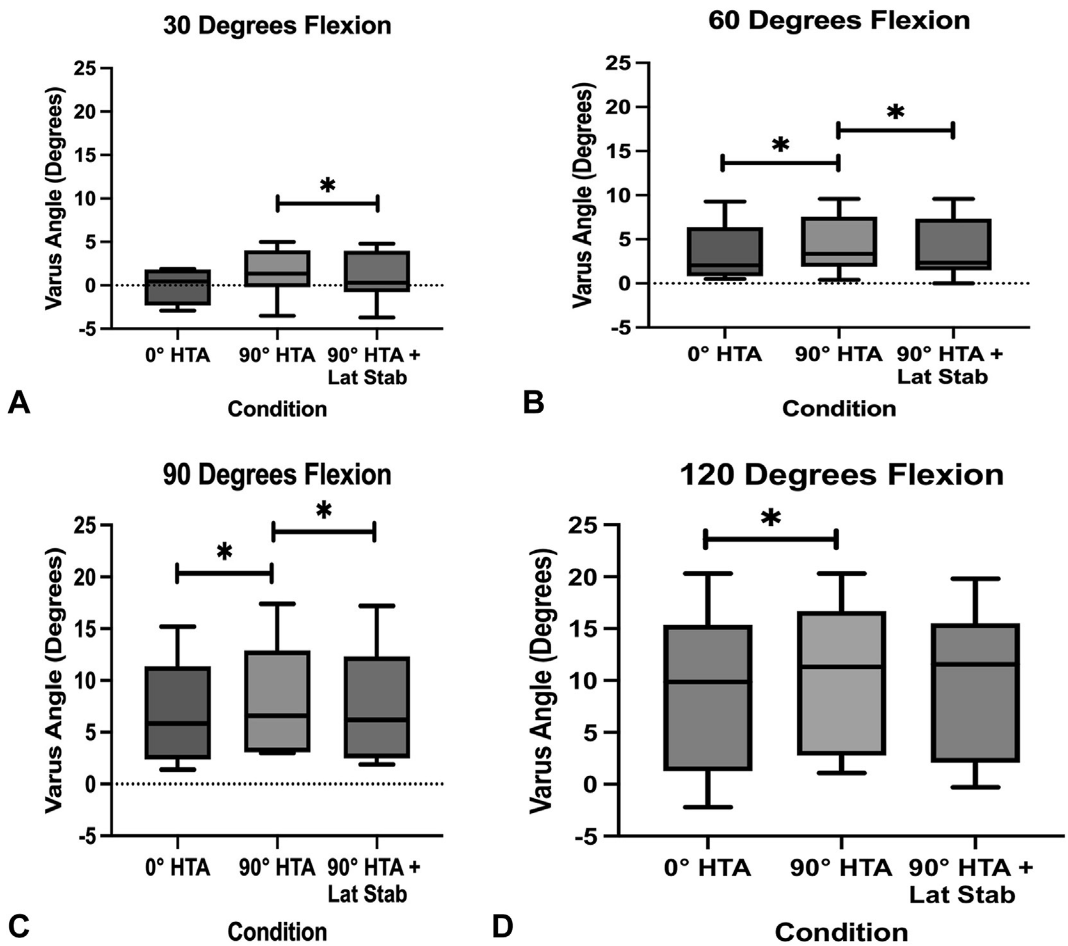

Figure 3. Box and whisker plots depicting elbow varus degree at (**A**) 30° (**B**) 60° (**C**) 90 °, and (**D**) 120° elbow flexion for three conditions: 0° HTA, 90° HTA, and (90° HTA) with lateral dynamic stabilizers active.

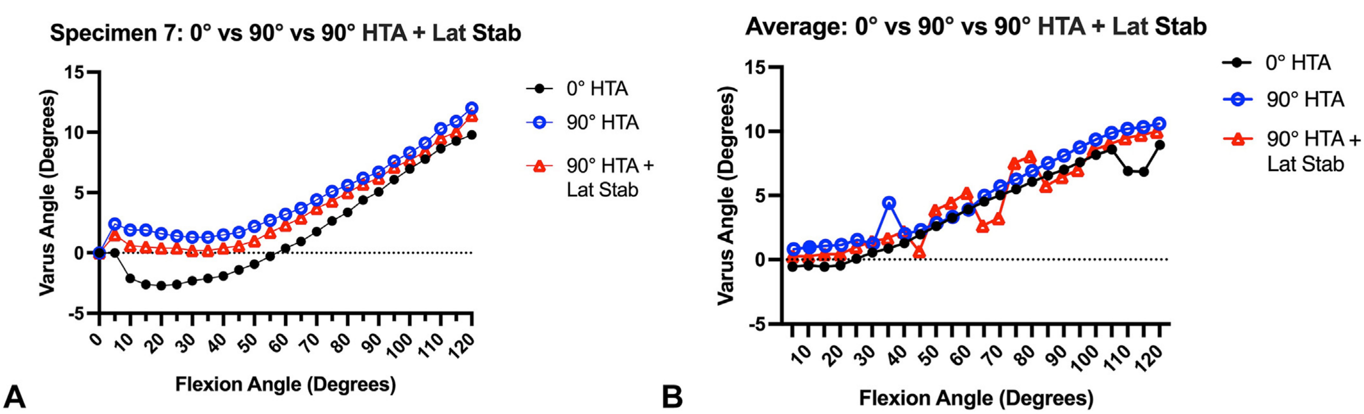

Figure 4. Varus angle degree at every 5° of elbow flexion for three conditions: 0° HTA, 90° of abduction (90° HTA), and 90° HTA with lateral dynamic stabilizers active (90° HTA + Lat Stab) for (**A**) Specimen 7, a representative sample, and (**B**) aggregate data of all specimens.

measurements were taken based on the position of the humerus and ulna with a 120 frames per second sample rate and an accuracy within 0.8 mm of translation and 0.8° of rotation.

Joint motion and muscle forces

The biceps, brachialis, brachioradialis, triceps, flexor/pronator, and extensor mass were simulated with muscle force combinations based on previously recorded EMG and physiological cross-sectional area measurements.[8,10] Three different muscle force combinations were used to simulate three different conditions: (1) 0° HTA, (2) 90° HTA, and (3) 90° HTA + Lat Stab. In the first condition, total force was increased until smooth motion occurred using a muscle force combination that distributed force to the biceps (0.31), brachialis (0.42), brachioradialis (0.11), and triceps (0.16) tendons, making the brachialis the primary flexor. In the second condition, 90° HTA, to account for the influence of gravity as the arm is abducted away from the body, a decreasing force was required to flex the elbow. Thus, the muscle forces in the flexors were decreased, and the force in the extensors was increased to maintain a similar motion profile. The flexor load was multiplied by 0.5 and the extensor load by 0.75.[17,21] In the third condition, (90° HTA + Lat Stab), an additional 50 N was applied to the lateral stabilizers with an origin at the medial epicondyle.[17,18]

Data analysis

All varus-valgus kinematic data were reported as a varus angle in reference to the starting position at each abduction angle so that the varus-valgus angle in full extension was considered 0°. Elbow varus angle was recorded continuously and then analyzed at 30°, 60°, 90°, and 120° of flexion. The primary outcome parameter was the difference in varus angle between conditions at each respective flexion angle.

Statistical method

A Shapiro-Wilk test for normal distribution was performed, followed by a two-way repeated measures analysis of variance to compare varus angle in three conditions: 0° HTA, 90° HTA, and 90° HTA + Lat stab and evaluate if varus angle at any of the four flexion angles differed from the others between the conditions. The P value of < .05 was considered statistically significant.

Results

Result 1

There were no bony abnormalities on fluoroscopic examination, and all elbows had a supple and full range of motion. No soft tissue instability was present.

Result 2

Data were normally distributed in each condition and flexion angle, determined by Shapiro-Wilk test, $P > .05$. Elbows underwent a loss of valgus carrying angle in all three conditions: 0° HTA, 90° HTA, and 90° HTA + Lat Stab. The varus angle versus flexion curve demonstrated little varus angle change in early flexion before 40°, and the most change occurred in the midrange of flexion, 30° to 90°. Among the varus angle versus flexion curves, the most variability occurred when the lateral dynamic stabilizers were activated (90° HTA + Lat Stab). In general, variability of the varus angle increased at increasing flexion angles (Figs. 3 and 4).

Result 3.1

Our data demonstrated a significant increase in elbow varus angle means between the conditions 0° and 90° HTA throughout active flexion at 60°, 90°, and 120° flexion, but not at 30° flexion. At 60° of flexion, there was a 0.9° change in varus ($P = .04$), 3.4° ± 3.4° versus 4.3° ± 3.3°, respectively. At 90°of flexion, there was a 1.1° change in varus ($P = .01$), 6.9° ±5.1° versus 8.0° ± 5.5°, respectively. At 120° of flexion, there was a 1.6° change in varus ($P = .02$), 8.9° ± 8.0° versus 10.5° ± 7.3°, respectively. At 30° of flexion, there was a nonsignificant 0.8° change in varus ($P = .07$), 0.7° ± 2.1° versus 1.5° ± 2.9°, respectively (Fig. 3).

Result 3.2

Our data demonstrated a significant decrease in elbow varus angle between the conditions 90° HTA and 90° HTA + Lat Stab throughout active flexion at 30°, 60°, and 120° flexion, but not at 120° flexion. At 30° of flexion, there was a −0.6° change in varus ($P = .03$), 1.5° ± 2.9° versus 0.9° ± 3.0°, respectively. At 60° of flexion, there was a −0.5° change in varus ($P = .03$), 4.3° ± 3.3° versus 3.8° ± 3.6°, respectively. At 90°of flexion, there was a −0.4° change in varus ($P = .02$), 8.0° ± 5.5° versus 7.6° ± 5.7°, respectively. At 120° of flexion, there was a nonsignificant −0.6° change in varus ($P = .21$), 10.5° ± 7.3° versus 9.9° ± 7.4°, respectively (Fig. 3).

Result 3.3

Our data demonstrated no significant difference in elbow varus angle at any elbow flexion angle between conditions 0° HTA and 90° HTA + Lat Stab (Fig. 3). Varus angle means between these conditions, however, did increase by 0.2°, 0.4°, 0.7°, 1.0°, at 30°, 60°, 90°, and 120° flexion, respectively.

Discussion

Six specimens were dissected and actuated to successfully recreate elbow motion with the arm abducted (90° HTA), and again abducted, but with the lateral stabilizers actuated (90° HTA + Lat Stab), so as to recreate the influence of lateral forearm-originating dynamic stabilizers. We contrasted varus angle in these two conditions with the varus angle at the arm at the side position (0° HTA) to identify the effect of both abduction and dynamic lateral stabilization on elbow biomechanics. Arm abduction created a greater elbow varus angle when compared with the arm at the side, and activation of the dynamic lateral stabilizers counteracted the effect of gravity, so that the varus angle throughout flexion was restored to the arm at side position (0° HTA).

Muscle force combination

The experimental setup (DETA) (Fig. 1) has previously demonstrated repeatability in creating smooth motion at different HTA angles by using arm abduction-dependent muscle force combinations. The combination of the arm at the side position (0° HTA) creates a greater elbow flexion force to overcome the resisting torque created by the weight of the arm.[17] The muscle force combination for the abducted arm position (90° HTA) creates a smaller elbow flexion force because the weight of the arm does not generate a torque that needs to be overcome to flex the arm and instead this torque causes a coronal plane tensioning of the lateral ligaments.[17] One other experimental setup that also employs active motion to study elbow biomechanics similarly required more muscle force to flex the elbow in the arm at side position (0 HTA).[21]

At side position (0° HTA)

A flexion versus varus angle curve with the arm at the side has already been characterized, which demonstrated a loss of valgus carrying angle as the elbow was flexed from the extended position.[17,18] It was shown that at this position (0° HTA), most varus angle changes occurred between 30° and 90° of flexion.[18] This finding suggests that bone morphology and joint congruity contribute to a decrease in valgus angle throughout flexion. The joint's ability to maintain congruence during motion is contributed to by the ligament and capsule integrity as well as dynamic stability imparted by the muscles that cross the elbow. The dynamic stability is substantial in this arm at side position because a large force is required to flex the elbow.

Abducted arm (90° HTA)

When the arm was abducted (90° HTA), a different muscle force combination was used, which required less flexion force, lessening the dynamic stability. Decreased dynamic stability coupled with the torque created by the weight of the cadaver forearm affected the varus angle during flexion whereby the elbow experienced a varus change that averaged 8.86° from the extended elbow to 120° of flexion (change in carrying angle). When comparing 0° HTA with 90° HTA, an average of 1.2° greater varus angle was recorded throughout flexion. This change was prevalent at all flexion angles except 30° flexion. The loss of significance at 30° flexion could be due to detecting a 1° to 3° difference with SDs that are larger.

Although the flexion versus varus angle curves at 90° HTA did demonstrate an increased varus angle when compared with 0° HTA, the two varus versus flexion angle curves were similar in appearance. This is likely because the soft tissue support of the elbow was preserved in these cadaver specimens, and the intact soft tissue structures resisted what would otherwise have been greater varus deflection during arm abduction (90° HTA). We believe that the soft tissue support is relied upon to counter the varus torque as well as the decreased dynamic stability that occur when the arm is abducted, thus allowing overall maintenance of bony congruence.[3,18] As the varus torque tensions the lateral side, the soft tissue structures stretch in their attempt to prevent further lateral gapping and their individual ability to do so influences the motion profile of each specimen.[17] Previous biomechanical studies have demonstrated varus-valgus and axial laxity of up to 4° in the intact elbow.[10,16,22–25]

Abducted arm with lateral stabilizers active (90° HTA + Lat Stab)

The actuation of the lateral forearm stabilizing muscles affected the varus angle during flexion of the elbow. Comparing the abducted arm with and without activation of the lateral forearm-originating muscles, the lateral stabilizers decreased the varus that the abducted elbow experienced at 30°, 60°, and 90°. No significant difference was noted at 120° of flexion. The loss of significance at 120° of flexion could be due to detecting a 1° to 3° difference with standard deviations being larger than that. Our results agree with an EMG study that demonstrated the lateral forearm muscles to be active during arm abduction to offset the loss of dynamic stability that is created by less force being required to flex and extend the elbow.[8]

We compared the varus angle during flexion curve of the elbow in the abducted arm with activation of the lateral forearm-originating muscles to those obtained with the arm at side (0 HTA) position and observed no significant difference. This suggests that activation of lateral stabilizers in the abducted arm (90 HTA) restored a motion pattern to resemble that of the nonabducted arm. Activation of the lateral forearm-originating muscles in the abducted position, such as when reaching out to grab an object, may decrease the tension on the lateral ligaments.

Strengths and limitations

A strength of our study is that active motion was generated by simulating the dynamic stabilizers across the elbow. One other experimental setup employed active flexion through the reproduction of humeral-originating muscles and demonstrated that the elbow tracks in less varus during active motion than during passive flexion in the arm abducted position (90 HTA), but they did not evaluate the effect of lateral dynamic stabilizers.[7,21]

Limitations of the study include that not enough torque was created by only using the weight of the arm and not applying an additional weight in hand. Our restricted loading prevented failure of the bone clamping mechanism as well as the tendons to cable fixation during the many active loading cycles that were required by this experiment. Another limitation is that the forearm and wrist were fixed in neutral, which may alter elbow kinematics.

Although we measured consistently greater varus angles in the abducted arm when compared with the nonabducted arm, our measurements only represented small angular changes. This is to be expected, given that the capsule and collateral ligaments were preserved in our cadavers and are expected to, therefore, maintain joint congruency. Had we destabilized the elbow by transecting the ligaments, then a larger angular change would likely have been measured.

Significance

Our model establishes the anatomic decrease in valgus angle by flexion angle in vitro and the effect of abduction and forearm muscle dynamic stabilization. The clinical significance of these findings is to provide a baseline for the change in elbow varus angle in the intact elbow when abducting the arm, as well as the contribution of lateral dynamic stabilizers. This change may contextualize the biomechanical analysis of arthroplasty and ligamentous reconstruction designs in the dependent and abducted arm positions. Current semiconstrained elbow arthroplasty designs aim for the mechanical hinge to exhibit more built-in laxity than the stability, conferred by the native ligaments.[26] Given that arm abduction creates a varus torque and tightens the lateral soft tissue support, inadequate soft tissue constraint may place the elbow outside of its range of built-in laxity. Future elbow arthroplasty designs may benefit from incorporating methods of maintaining or restoring the native soft tissue laxity within what is allowed by the hinge. Given the importance of the forearm muscles and their ability to provide lateral stabilization to the elbow, an emphasis should be made during arthroplasty to maintain their origin from the epicondyle, particularly in fracture settings where the distal humerus fragments may be simply removed prior to implantation.

Conflicts of Interest

No benefits in any form have been received or will be received related directly to this article.

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