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Original Research

A Dynamic Elbow Testing Apparatus for Simulating Elbow Joint Motion in Varying Shoulder Positions

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Purpose: To develop and evaluate the capabilities of a dynamic elbow testing apparatus that simulates unconstrained elbow motion throughout the range of humerothoracic (HTA) abduction.
Methods: Elbow flexion was generated by six computer-controlled electromechanical actuators that simulated muscle action, while six degree-of-freedom joint motion was measured using an optical tracking device. Repeatability of joint kinematics was assessed at four HTA angles (0°, 45°, 90°, 135°) and with two muscle force combinations (A1-biceps brachialis, brachioradialis and A2-biceps, brachioradialis). Repeatability was determined by comparing kinematics at every 10° of flexion over five flexion–extension cycles (0° to 100°).
Results: Multiple muscle force combinations can be used at each HTA angle to generate elbow flexion. Trials showed that the testing apparatus produced highly repeatable joint motion at each HTA angle and with varying muscle force combinations. The intraclass correlation coefficient was greater than 0.95 for all conditions.
Conclusions: Repeatable smooth cadaveric elbow motion was created that mimicked the in vivo situation.
Clinical relevance: These results suggest that the dynamic elbow testing apparatus can be used to characterize elbow biomechanics in cadaver upper extremities.

The elbow is moved and stabilized by muscles whose actions influence joint function.[1] In concert with static stabilizers, the muscles that cross the elbow exert dynamic stability via compressive forces that maintain the articular congruency during motion and decrease stress on the collateral ligaments.[2,3] Active elbow motion has been shown to be more repeatable compared to passive motion, which requires an examiner to manually flex and extend the arm.[4]

Active elbow motion has been characterized with the arm at the side position (0° of humerothoracic abduction [HTA]) as well as in 90° of HTA (abduction) and adduction.[3–6] The effect that 45° and 135° of HTA has on elbow kinematics has not been investigated. Data on these positions of HTA are needed to better understand elbow stability during activities of daily living.

The objectives of this study were to develop and characterize the capabilities of a dynamic elbow testing apparatus (DETA) for simulating unconstrained elbow motion throughout the range of HTA using full upper extremities. Thus, the technical capabilities of the testing apparatus and a sample application that includes a repeatability analysis are described.

Materials and Methods

Testing apparatus

Six electromechanical actuators (EMXG50188 – BE233 Series Servomotors and Acroloop controller, Aries Series, Parker) were used to apply individual forces or displacements to the tendon of

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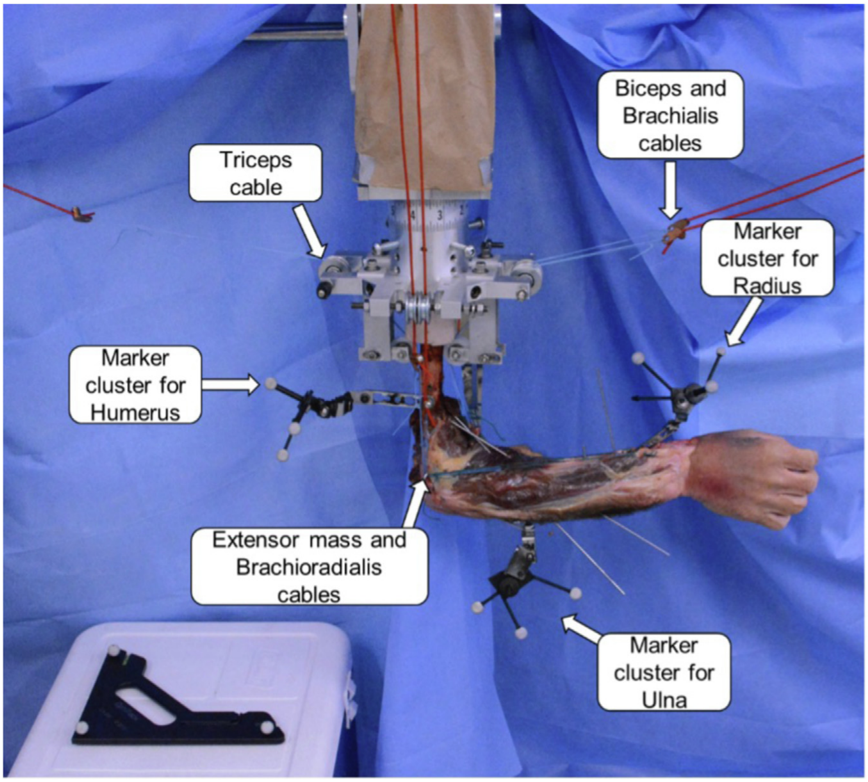

Figure 1. Dynamic elbow testing apparatus (DETA) with cadaver arm that is mounted at 0° of humerothoracic abduction (HTA). A cable pulley system can be positioned to ensure accurate simulation of each muscle force.

Table 1

Two Muscle Force Combinations Used to Flex the Elbow. A1 employs biceps (BI), brachialis (BR), brachioradialis (BRD), and triceps (TRI) for flexion based on electromyography (EMG) and physiological cross-sectional area (pCSA). A2 employs no brachialis[4,9,10]

	BI	BR	BRD	TRI
A1	0.31	0.42	0.11	0.16
A2	0.73	0	0.11	0.16

Table 2

The Effect of Gravity at Different Degrees of Humoral Thoracic Abduction (HTA). This effect contributes to the requirement for variable forces to be employed during flexion and extension of the elbow. An HTA muscle ratio was employed to ensure smooth elbow flexion and extension

	Degree of Humerothoracic Abduction			
	0°	45°	90°	135°
Flexor Load Ratio (applied to brachialis and biceps)	1	0.75	0.5	0.25
Extensor Load Ratio (applied to the triceps)	0.25	0.5	0.75	1

six muscles that cross the elbow using a suture clamp-cable-pulley system (Fig. 1). Force feedback is provided by load cells (MLP-300-CD, Transducer Techniques) that have an accuracy of 0.25% of rated output (2 mV/V) and are mounted on top of the piston of each actuator. Position feedback is accomplished using the controller of each actuator with an accuracy of 0.1 mm. The motion of each actuator is controlled independently in a closed feedback loop.

The DETA employs a specialized machine mount that positioned the humerus throughout the range of HTA. The humerus is potted in epoxy putty and mounted in a cylinder. The forearm is moved using a custom designed cable pulley system that can be positioned to the anatomic force vector of each simulated muscle. Tendon to cable fixation occurred using the Krackow suturing method.[7,8]

The simulated muscles were the two flexors (biceps and biceps brachialis), an extensor (triceps), a medial stabilizer (flexor-pronator mass) and two lateral stabilizers (extensor mass and brachioradialis). Before active motion trials began, the cables were tensioned at 5 N to account for physiological tension that occurs in muscles at rest.

Two muscle force combinations (A1, A2) were used to flex the elbow based on physiological cross-sectional area (pSCA) and electromyography (EMG) recordings of resisted isometric movements (Table 1).[4] In A1, force was applied to the biceps, brachialis, and brachioradialis, with the brachialis being the primary flexor. For example, in the A1 sequence at 0° of HTA, the force applied were 77.5 N to the biceps, 105 N to brachialis, 27.5 N to brachioradialis, and 40 N to the triceps. In A2, zero force was applied to the brachialis, which simulated an arm that was flexed primarily by the biceps. Maximum force was increased until smooth flexion was achieved.

To account for the influence of gravity as the arm is abducted away from the body, an additional muscle force combination was developed. As HTA increases, a decreasing force is required to flex the elbow. Thus, the muscle forces in the flexors were decreased and the force in the extensors increased to maintain a similar motion profile. This muscle force combination was created for 0°, 45°, 90°, and 135° of HTA. (Table 2).[4,9,10]

The specimen received five flexion and extension cycles between the neutral and fully flexed position. The neutral position, from which measurements were taken, was defined as the elbow in 0° of HTA and 0° of flexion and with 5 N applied to the tendons, except the triceps, which was activated to maintain elbow extension. The arm was always first flexed and extended at 0° of HTA and then abducted to 45°, 90° and 135° of HTA, sequentially. Force application began at zero and then increased linearly to the chosen value. At each HTA angle, the muscle forces, tendon excursions, and humeral position and orientation were recorded.

The maximum force applied within the system was limited to 250 N. Thus, in the A1 sequence at 0° of HTA, 77.5 N was applied to the biceps (Bi), 105 N to brachialis (BR), 27.5 N to brachioradialis (BRD), and 40 N to the triceps (TRI). The medial and lateral dynamic stabilizers remained actuated at 5 N to simulate resting tone throughout all muscle force combinations. The HTA muscle force combination modulated these forces as the arm was abducted so as to accommodate for the effect of gravity.

Motion measurement

Elbow motion was measured using a six degrees-of-freedom optical tracking system (Optitrack, Corvallis, Oregon, Flex 13) that uses multiple synchronized cameras that are positioned around the testing apparatus. Two-dimensional images were captured from each camera, and the overlapping position data were compared to compute the three-dimensional positions via triangulation. Marker triads were attached to the midbody of the humerus, ulna, and radius. Each triad was connected by a stainless steel extender to allow marker triad visibility from the tracking cameras.

The motion capture system has a 120 frames per second sample rate, and the accuracy in our laboratory's testing environment is within 0.8 mm of translation and 0.8 degrees of rotation. Previous studies have shown that this motion capture system, when quantifying ankle kinematics, produces highly repeatable tibiofibular joint motion.[11]

Coordinate system

The coordinate system to define the elbow motion followed the International Society of Biomechanics recommendations. The y axis of the humeral coordinate system (Ch) was defined as the line through the center of the bony shaft, and it was directed to the distal direction. The z axis of the Ch was defined as the line through the medial and lateral epicondyles, and it was directed to the medial direction. Finally, the x axis of the Ch was defined as a perpendicular line to both y and z axes and it was pointed to the anterior direction (Fig. 2). The origin of the humeral coordinate system was located at the midpoint of the line connecting the medial and lateral epicondyles. When the forearm extended to 0° of flexion, the forearm coordinate system was coincident with the humeral coordinate system and was fixed to the forearm.

Sample preparation and application

Fresh-frozen, full upper extremities were obtained without gross deformity on visual inspection. The specimens were stored at −20 °C and thawed at room temperature for 24 hours before dissection. Once thawed, the soft tissue proximal to the ulnohumeral joint was removed except for the tendons belonging to the humeral originating muscles. The soft tissue stabilizers of the elbow as well as the forearm muscles and skin were left intact. The origins of the flexor-pronator mass and the extensor mechanism were recreated via eyelet screws that were inserted into the lateral supracondylar ridge and the medial epicondyle of the humerus, respectively. Cables were passed through the eyelets.

The wrist and forearm were immobilized with K-wires in the neutral forearm position to create a rigid body below the elbow joint. The proximal humerus was potted in epoxy putty (Bondo, 3M) so that the humerus could be attached to the testing apparatus and maintain enough humeral shafts to allow full elbow flexion and extension (0° to 130° flexion).

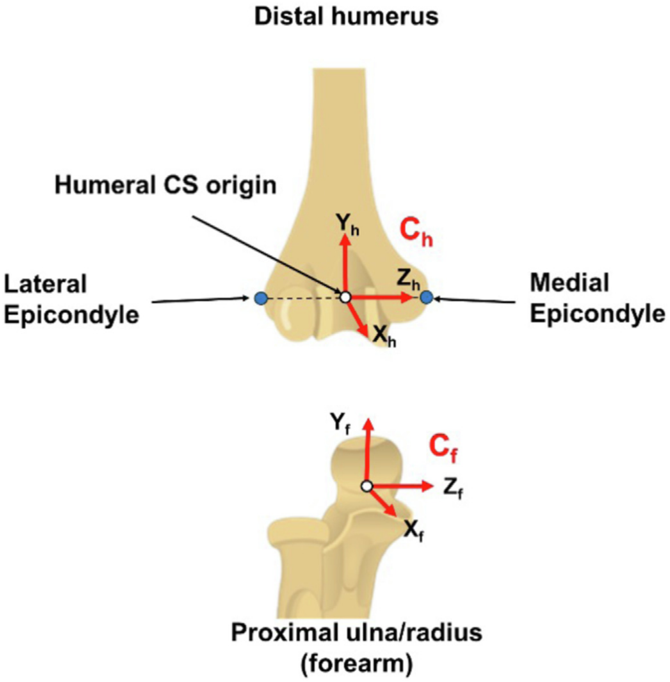

Figure 2. Alignment of the humeral coordinate system (Ch) and forearm coordinate system (Cf).

To examine measurement repeatability at four HTA angles, the elbow was moved with muscle force combinations (A1 = biceps, brachialis, brachioradialis; A2 = biceps, brachioradialis). The inactivated lateral and medial stabilizers had a 5 N force applied to their cables. Measurement repeatability was determined by comparing five flexion–extension (0° to 100°) cycles that were applied at each HTA (0°, 45°, 90°, 135°) and during both muscle force combination (A1–A2). During the test, three rotations (flexion–extension, internal–external, and varus–valgus) and three translations (medial–lateral, proximal distal, and anterior–posterior) were measured and the standard deviation for each parameter was calculated at every 10° of elbow flexion.

The statistical difference of the standard deviation (repeatability) in each flexion angle was examined using the F-test. Test-retest reliability was determined using intraclass correlation coefficients (ICC), which characterizes the extent to which outcomes within each measurement cluster are likely to be similar.

Results

At 0° of HTA with the A1 muscle force combination (flexed by biceps and brachialis forces), the internal–external (IE) rotation of the ulna became more external with increase of the flexion, and the maximum rotation of 7.2° external rotations was obtained at 100° of flexion. The varus–valgus (VV) rotation became more varus with increasing elbow flexion until 70° of flexion. The maximum varus rotation of 6° was obtained at 70 degrees of flexion, and then the varus rotation slightly decreased (Fig. 3). The data dispersion as determined by the F-test was 0.0 to 0.2 for both rotations and did not show a statistical change related to the increase in the magnitude of each motion. At the different HTA angles, the magnitude of both IE and VV rotation differed slightly from the side (0° HTA) position and ranged from 0.1° to 1.2°.

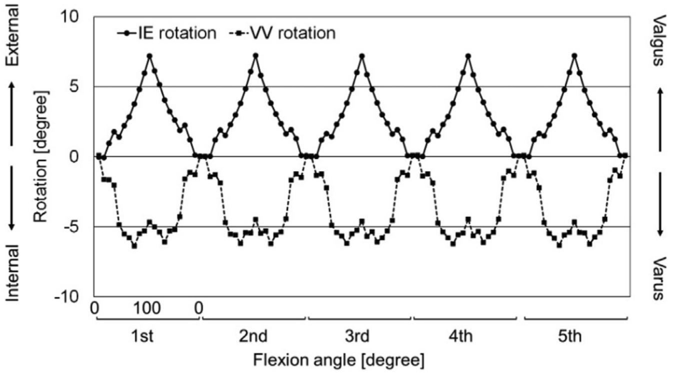

Figure 3. Internal–external and varus–valgus rotations recorded through five cycles of elbow motion at 0° of HTA with an A1 muscle force ratio.

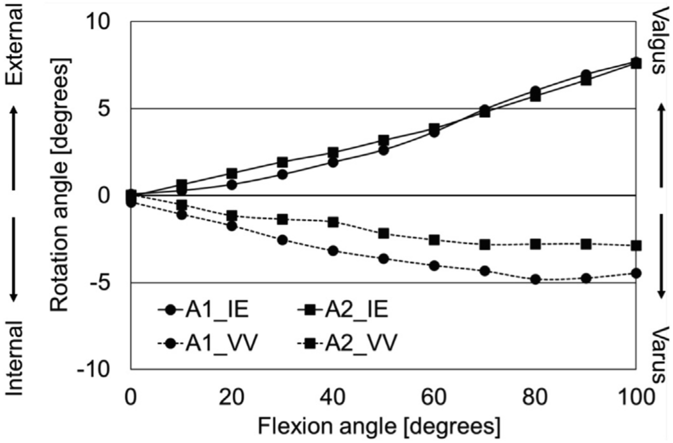

Figure 4. Internal–external and varus–valgus rotations during dynamic elbow flexion at 90° of humerothoracic abduction (HTA) with muscle force combinations (A1 and A2).

At 0° of HTA with the A2 muscle force combination (flexed by biceps force), the IE rotation became more external with the increase of flexion, and the maximum rotation of 7.5° was obtained at 100° flexion. The VV rotation became more valgus with the increase in flexion until 70° flexion. The maximum rotation of 6° was obtained at 70° of flexion, and then the rotation plateaued. The data dispersion as determined by the F-test was 0.0 to 0.4 for both rotations and did not show a statistical change related to the increase in the magnitude of each motion. In the different HTA angles, the magnitude of both IE and VV rotation differed only slightly from the at side position and ranged from 0.1° to 1.0°.

The ICC at each HTA angle and for each muscle force combination remained above 0.95. Smooth cadaveric elbow motion was observed that mimicked the in vivo situation (Fig. 4, Tables 3 and 4).

Table 3
Repeatability of Internal–External and Varus–Valgus Rotations for Every 10° of Elbow Flexion at 45°of HTA

FE (degree)	IE (degree)	VV (degree)
0	0.1	0.0
10	0.1	0.0
20	0.1	0.1
30	0.1	0.1
40	0.2	0.3
50	0.1	0.0
60	0.0	0.0
70	0.0	0.0
80	0.0	0.1
90	0.0	0.0
100	0.1	0.0

FE, elbow flexion-extension; IE, internal–external rotation; VV, varus–valgus rotation.

Table 4
Repeatability of Internal–External and Varus–Valgus Rotations for Every 10° of Elbow Flexion at 135° of HTA

FE (degree)	IE (degree)	VV (degree)
0	0.1	0.1
10	0.1	0.1
20	0.1	0.1
30	0.1	0.1
40	0.1	0.1
50	0.1	0.1
60	0.1	0.1
70	0.0	0.1
80	0.0	0.1
90	0.0	0.1
100	0.1	0.1

FE, elbow flexion-extension; IE, internal–external rotation; VV, varus–valgus rotation.

Discussion

Our DETA reproduces active elbow motion by simulating muscle forces and measuring joint kinematics at 0°, 45°, 90° and 135° of HTA. Active motion generates compression of the ulnohumeral joint, which dynamically stabilizes the elbow and offloads the soft tissue.[3] Our experimental setup aimed to reproduce the mechanism by which the elbow is stabilized in vitro.[12] Another testing apparatus has also demonstrated repeatable elbow kinematics with different muscle force combinations but does not include 45° and 135° HTA.[4]

This technical report describes a DETA that demonstrates highly reproducible flexion of the elbow when different muscle force combinations (A1, A2) were used. Motion of the elbow was achieved throughout the range of HTA angles using multiple muscle force combinations and incorporated the effect that gravity exerts on the arm. Successful characterization of joint kinematics during simulated elbow motion throughout the range of HTA permits the establishment of a test platform to compare changes in joint motion that may result from manipulation of individual variables (eg, forces to a given muscle, collateral ligament tears, joint alterations).

Strength of this experimental setup was that an entire upper extremity was used in the biomechanical evaluation of elbow joint motion because the true inertial properties of the upper extremity are represented during elbow motion.

A limitation of this study was that only one specimen was used to assess for the repeatability across five flexion–extension (0° to 100°) cycles at 4 HTA angles (0°, 45°, 90°, and 135°) while using two muscle force combinations (A1-A2). However, favorable ICC were identified, and our reliability results would likely not have changed with more specimens.

Future investigative efforts will include characterization of the effects on the kinematics due to the medial and lateral elbow stabilizers. We will also evaluate the biomechanical changes that may occur after muscular and ligamentous deficiencies have been introduced or after soft tissue repair/reconstruction or arthroplasty. The ability to simulate an overhead position, in which the arm is placed in 135° of HTA, will allow simulation of kinematics that are common to throwing motions.

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