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Overhead arm positioning in the rehabilitation of elbow dislocations: An *in vitro* biomechanical study

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ABSTRACT

Study Design: In vitro biomechanical study.
Introduction: Elbow stiffness is a common complication following elbow dislocation. Overhead exercises have been proposed to initiate early motion to reduce stiffness through employing gravity to stabilize the elbow. The implications of this position with regard to elbow kinematics after dislocation have not been reported.
Purpose of the Study: To determine the influence of the overhead position on elbow stability following combined medial and lateral collateral ligament (MCL and LCL) injuries.
Methods: Passive and simulated active extension were performed on 11 cadaveric elbows with the arm in the overhead, dependent, and horizontal positions and with the forearm in pronation, neutral, and supination. Internal-external rotation (IER) and varus-valgus angulation (VVA) of the ulnohumeral joint were assessed for the intact elbow and after simulated MCL-LCL injury. Repeated-measures analyses of variance were conducted to analyze the effects of elbow state, arm position, forearm rotation, and extension angle.
Results: During passive extension with the arm overhead, the pronated position resulted in more internal rotation than supination (-2.6 ± 0.7°, P = .03). There was no effect of forearm rotation on VVA. The overhead position increased internal rotation relative to the dependent position when the forearm was neutral (-8.5 ± 2.5°, P = .04) and relative to the horizontal position when the forearm was supinated (-12.7 ± 2.2°, P= .02). During active extension, pronation increased valgus angle compared to the neutral (+1.2 ± 0.3°, P= .04) and supinated (+1.5 ± 0.4°, P= .03) positions, but did not affect IER. There was no difference between active and passive motion with the arm overhead (P > .05).
Discussion: Movement of the injured elbow in the overhead position most closely replicated kinematics of the intact elbow compared to the other arm positions.
Conclusions: Overhead elbow extension results in similar kinematics between an intact elbow and an elbow with MCL and LCL tears. As such, therapists might consider early motion in this position to reduce the risk of elbow stiffness after dislocation.

Introduction

The elbow is the second most frequently dislocated major joint in adults.[1] Elbow dislocations comprise 10%-25% of all elbow injuries and occur in approximately five per 100,000 persons annually.[2] Dislocations result in damage to the lateral collateral ligament (LCL) and medial collateral ligament (MCL) of the elbow, which can result in persistent and disabling elbow instability.[3,4] Dislocations may be classified as simple or complex, characterised

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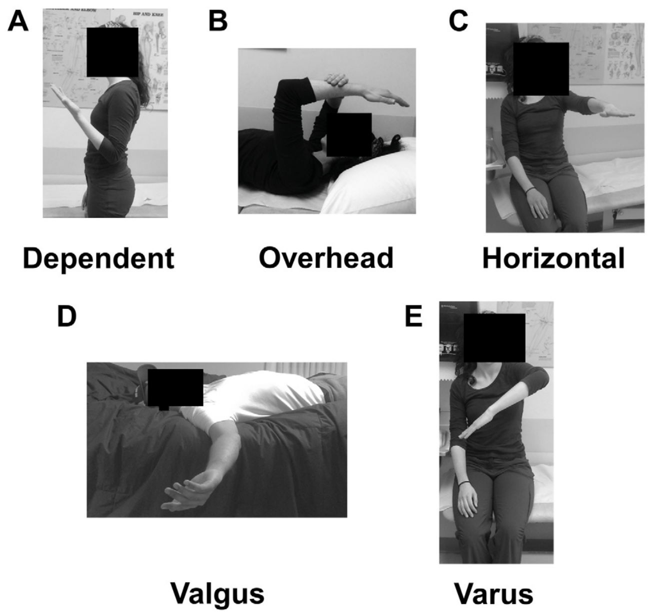

Fig. 1. Gravity-loaded arm positions. The arm can be positioned in the gravity-loaded dependent (A), overhead (B), horizontal (C), valgus (D), or varus (E) positions. (Image adapted with permission from: Manocha RHK, Kusins JR, Johnson JA, King GJW. Optimizing the rehabilitation of elbow lateral collateral ligament injuries: a biomechanical study. *J Shoulder Elb Surg.* 2017;26(4):596-603).

by the absence or presence of fractures, respectively.[1,4,5] Simple dislocations are managed non-operatively with closed reduction, typically in the emergency department.[6] Complex dislocations often require open reduction with repair of associated fractures, ligaments, and the elbow capsule.[7] Following closed reduction or surgery, elbow stability is assessed to determine the optimal rehabilitation protocol.[1] If the elbow is stable, unrestricted active motion is permitted.[7] When there is post-reduction instability, extension is initially limited to prevent re-dislocation while full flexion is permitted.[7]

The position of the arm results in different gravitational moments about the elbow due to the weight of the forearm and hand (Fig. 1), and thus arm position may influence elbow stability.[8] In the dependent position, the shoulder is in neutral abduction/adduction and neutral rotation, and elbow flexion occurs in the coronal plane. In the horizontal position, the shoulder is flexed and in neutral rotation, and elbow flexion occurs in a plane perpendicular to the humerus. In the varus position, the shoulder is flexed and internally rotated, causing elbow flexion to occur in the same plane as the humerus. In the valgus position, the shoulder is abducted and externally rotated, causing elbow flexion to occur in the same plane as the humerus. Previous research has shown that in combined LCL and MCL-injured elbows, ulnohumeral kinematics during active extension in the gravity-loaded dependent and horizontal positions is similar to the intact elbow, suggesting that these are optimal positions for rehabilitation following elbow dislocations.[6] Prior research has also suggested that active and passive motion in the gravity-loaded varus and valgus positions results in significant instability in elbows with combined MCL and LCL injury.[6] Thus, patients are advised to avoid the varus and valgus arm positions following an elbow dislocation.[7]

Elbow stiffness is the most common complication of elbow dislocation.[9] As such, early range of motion is important, but elbow stability must not be risked, as it may lead to persistent instability and pain.[7,10,11] More recently some authors have recommended that patients perform elbow extension exercises with the arm overhead to maintain elbow stability while allowing full range of motion.[7] It is thought that the force of gravity from the weight of the forearm enhances articular compression in this position, increasing joint congruency and thus stability. The success of the overhead position has been reported in the setting of isolated LCL injury,[12] but has not been confirmed biomechanically in combined LCL and MCL injury.

After elbow dislocation, aggressive passive motion is avoided early on in the rehabilitation course, as it may be cause swelling, pain, re-dislocation, and heterotopic ossification.[1,6,7,9] Passive motion is typically introduced at 6 weeks and progressive strengthening is initiated at 8 weeks post-injury.[7] Previous studies have shown that active motion is more stable than passive motion in the case of MCL-deficient,[13] LCL-deficient,[14] and combined MCL-LCL deficient elbows[6] when the arm is in the dependent and horizontal positions. The role of muscle activation in the overhead position has not been determined with combined MCL-LCL deficient elbows.

The optimal position of the forearm during rehabilitation depends on the degree of MCL and LCL injury. Elbow dislocations have been reported to result in a progression of injury either from lateral to medial structures with injuries that occur when the elbow is flexed,[15] or from medial to lateral structures when injuries result from elbow extension with a valgus load.[3,16] If more lateral structures are damaged, pronation is recommended post-injury.[14,17-19] If more medial structures are damaged, supination is recommended.[13,20] If both the MCL and LCL are severely injured, neutral forearm positioning has been proposed during exercises[7] but the impact of this position has not been experimentally validated.

Purpose of the study

The purpose of this biomechanical *in vitro* investigation was to quantify elbow stability during simulated rehabilitation exercises with the arm in the dependent, overhead, and horizontal arm positions and with the forearm in pronation, neutral, and supination, before and after combined MCL-LCL injury. It was hypothesized that with combined MCL-LCL injury rehabilitation with the arm overhead would reduce instability compared to the dependent and horizontal arm positions. It was also hypothesized that neutral forearm positioning would reduce instability compared to the pronated and supinated positions, and that simulated active motion would reduce instability compared with passive motion.

Methods

Eleven fresh-frozen cadaveric left upper extremities (mean age ± standard deviation: 76 ± 11 years; four male) stored at –20°C were used. All specimens had been donated for scientific research and testing followed the guidelines of the Lawson Health Research Institute. Specimens were amputated at the forequarter level and thawed at room temperature (22 ± 2°C) prior to testing in a custom elbow motion simulator (Fig. 2).[12,21-23] In order to simulate active motion, braided Dacron (Gamefish Technologies, Newport Beach, California, USA) was used to suture the distal tendons of the biceps, brachialis, brachioradialis, pronator teres, triceps, wrist extensors (extensor carpi ulnaris and radialis longus) and wrist flexors (flexor carpi ulnaris and radialis) in a running locking fashion. For the brachioradialis, an alignment guide was placed at the supracondylar ridge. Similarly, guides were placed at the lateral epicondyle for the wrist extensors and at the medial epicondyle for the pronator teres and wrist flexors. Stainless

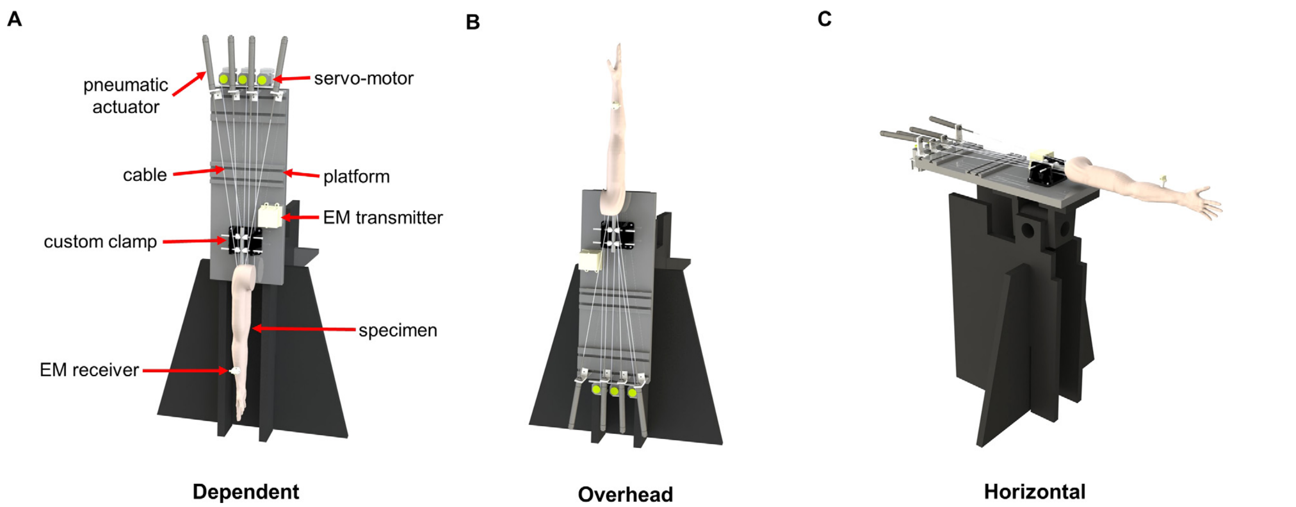

Fig. 2. Custom elbow motion simulator, in three positions. (A) The components of the custom simulator are shown with the humerus in the gravity-loaded dependent position. Stainless steel cables connected selected tendons of the upper extremity to servomotors and pneumatic actuators. A computer enabled simulated active elbow extension. An electromagnetic (EM) tracking system, with a transmitter fixed relative to the humerus and a receiver attached to the ulna, measured ulnohumeral kinematics. The platform could rotate to allow the humerus to also be positioned in the (B) overhead and (C) horizontal positions. A right upper limb is shown. (Image adapted with permission from: Manocha RHK, Kusins JR, Johnson JA, King GJW. Optimizing the rehabilitation of elbow lateral collateral ligament injuries: a biomechanical study. *J Shoulder Elb Surg*. 2017;26(4):596-603).

steel cables were connected to the sutures. These were then connected to computer-controlled servomotors (for biceps, brachialis, and triceps) and pneumatic actuators (for the remaining tendons). For each specimen, the humeral head was reamed and a custom-fabricated stainless-steel rod was inserted and cemented with methylmethacrylate into the medullary canal. This rod was secured to a clamp at the simulator base. The simulator base could be rotated to place the arm in the dependent, overhead, and horizontal positions.

Simulated passive motion was performed by one investigator (RM) manually grasping the wrist and hand to passively rotate the forearm into a fully pronated, neutral, or fully supinated position. The elbow was then carefully extended from full flexion to full extension at approximately 10° per second while maintaining the forearm in its pronated, supinated, or neutral position. Active elbow extension at a rate of 10° per second was then simulated using a custom-designed LabVIEW program that has previously been described through tensioning relevant tendons (National Instruments, Austin, Texas, USA).[12,22] A 10-N tone load was applied to the wrist extensors and the wrist flexors during active motion to stabilize the wrist.

Specimens were tested in the dependent, overhead, and horizontal positions. For each arm position, passive and active elbow extension were performed with the forearm in the pronated, supinated, and neutral positions. Testing was first conducted with the elbow intact. To simulate an elbow dislocation (“Injured” state), the LCL and common extensor origin were sectioned off the lateral epicondyle and the MCL and common flexor-pronator origin were sectioned off the medial epicondyle. The anterior joint capsule was also sectioned. The testing sequence was then repeated. Normal saline solution was used to keep the specimens moist and the skin was closed during testing. Five passive and five active preconditioning cycles through a full arc of flexion and extension were conducted prior to data collection to minimize viscoelastic effects.

A 6° of freedom electromagnetic tracking system (Flock of Birds, Ascension Technologies, Burlington, Vermont, USA) was employed to quantify motion of the ulna relative to the humerus, as has been previously described.[12,21–23] The transmitter was fixed to the simulator base and the receiver was fixed to the distal medial ulna. Following testing, the radiocarpal joint was disarticulated and anatomically-derived humeral and ulnar coordinate systems were established from the average of three successive digitizations of bony landmarks using a Delrin stylus attached to another receiver. The humeral coordinate system was established from the centre of the humeral shaft, the centre of curvature of the capitellum using a least-squares sphere-fit, and the centre of the trochlear groove using a least-squares circle-fit. The ulnar coordinate system was established from the centre (using a least-squares circle-fit) and plane of the greater sigmoid notch and the ulnar styloid tip.

Elbow instability was quantified at each extension angle by varus-valgus angulation (VVA) and internal-external rotation (IER) of the ulna relative to the humerus, determined using an Euler Z-X-Y sequence. The effects of active and passive motion, forearm rotation, and arm position on elbow stability for each elbow state (intact and injured) were analyzed using two-way repeated-measures analyses of variance (RM-ANOVA). Testing was carried out using SPSS (Chicago, Illinois, USA). For all tests, statistical significance was set at $\alpha = 0.05$ and Bonferroni adjustments were used for post hoc comparisons. A previous investigation in our laboratory suggested that a sample size of eight would be sufficient to look for differences by elbow state.[6]

Results

Dependent position

During passive motion (Fig. 3), there was no significant effect of ligament sectioning on VVA for all forearm positions ($P > .05$, Table 1). However, ligament sectioning increased internal rotation with the forearm pronated (mean ± SEM: -4.6 ± 0.4°, $P = .01$) and increased external rotation when the forearm was neutral (+5.6 ± 2.4°, $P = .03$) and supinated (+8.7 ± 1.8°, $P < .01$). Within the injured (ie, MCL-LCL deficient) elbow condition, forearm rotation did not affect VVA ($P = .27$). However, forearm rotation had a significant effect on IER ($P < .01$), with each condition being significantly different from the others and with pronation most closely replicating kinematics of the intact elbow.

During active motion, when the forearm was neutral, valgus angulation increased with ligament sectioning (+0.8 ± 0.6°, $P = .04$), but did not change with forearm supination or pronation ($P > .05$).

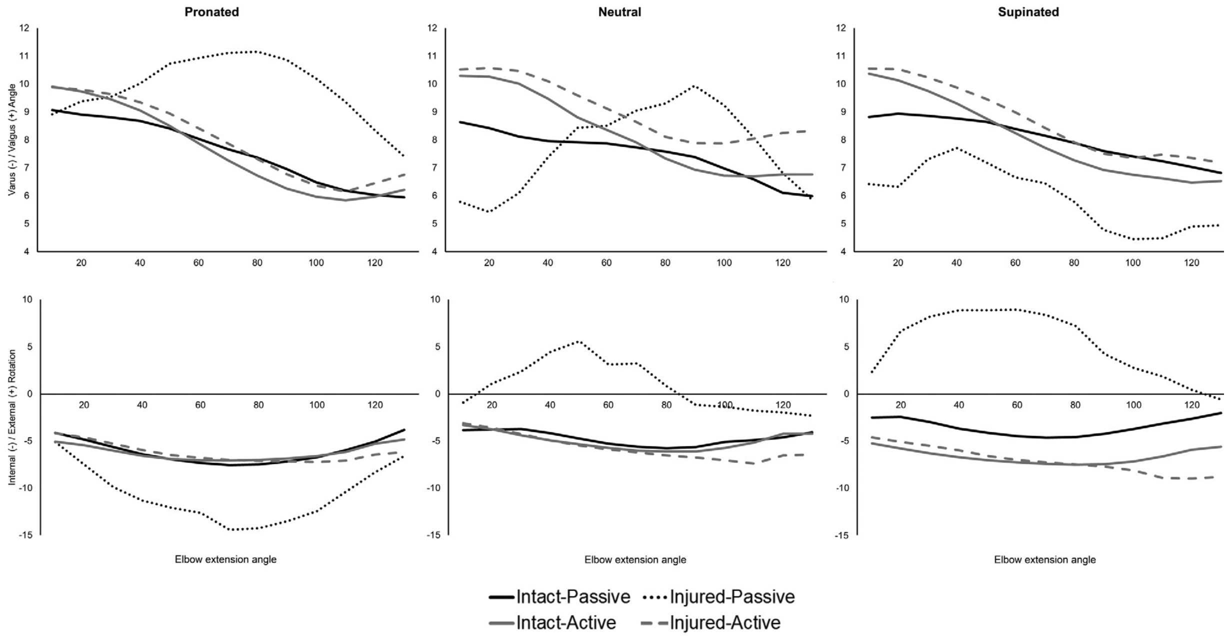

Fig. 3. Mean kinematic profiles with the arm in the dependent position. Varus-valgus angulation (top) and internal-external rotation (bottom) are shown with the forearm in pronation (left), neutral (middle), and supination (right). Four elbow states are shown: intact elbow during passive motion (intact-passive; black, solid); intact elbow during active motion (intact-active; grey, solid); elbow dislocation during passive motion (injured-passive; black, dotted); and elbow dislocation during active motion (injured-active; grey, dashed).

Table 1
Mean varus-valgus angulation (VVA) and ulnohumeral rotation (UHR) ± SD during elbow extension with the arm in the dependent position.

			Elbow state			
	Muscle activation	Forearm rotation	Intact	Injured	*P*	*P'*
VVA	Active	Pronated	7.6 ± 7.1°	8.0 ± 6.9°	.51	.02*
		Neutral	8.2 ± 7.4°	9.0 ± 8.0°	.04*	
		Supinated	8.1 ± 7.1°	8.7 ± 7.1°	.24	
	Passive	Pronated	7.6 ± 6.4°	9.8 ± 9.6°	.26	.27
		Neutral	7.5 ± 7.4°	7.7 ± 10.3	.90	
		Supinated	8.0 ± 6.5°	6.0 ± 9.3°	.15	
UHR	Active	Pronated	-6.2 ± 10.6°	-6.3 ± 10.5°	.80	.18
		Neutral	-5.0 ± 10.9°	-5.7 ± 10.9°	.21	
		Supinated	-6.6 ± 10.6°	-7.1 ± 10.4°	.30	
	Passive	Pronated	-6.1 ± 9.9°	-10.7 ± 10.3°	.01*	<.001*
		Neutral	-4.7 ± 9.8°	0.87 ± 12.2°	.03*	
		Supinated	-3.5 ± 8.7°	5.2 ± 10.5°	<.001*	

P-values describe the significance of elbow state as the result of a two-way repeated-measures analysis of variance (2WRMANOVA) with elbow state (intact, injured [medial and lateral collateral ligament injury]) and extension angle as variables. *P*'-values describe the significance of forearm rotation in the injured case as the result of a two WRMANOVA with forearm rotation (pronated, neutral, supinated) and extension angle as variables.

* Indicates significance ($P < .05$).

There was no effect of ligament sectioning on IER with the forearm in any position ($P > .05$). In the injured elbow, forearm rotation affected VVA ($P = 0.02$). However, pairwise comparisons between forearm rotations showed no significant differences ($P > .05$). Pronation most closely replicated kinematics of the intact elbow. In the injured condition, forearm rotation did not change IER ($P > .05$). Injured elbow kinematics more closely matched the intact elbow during active motion more than passive motion for all forearm positions for IER ($P = .02$ for pronation, $P = .02$ for neutral, and $P < .001$ for supination). However, for VVA, this only reached statistical significance for pronation ($P = .03$).

Overhead position

During passive motion (Fig. 4), ligament sectioning did not affect VVA while the forearm was pronated and in neutral ($P > .05$, Table 2). However, ligament sectioning increased valgus angulation when the forearm was supinated (+1.8 ± 1.0°, $P = .02$). Ligament sectioning increased external rotation for all forearm positions (pronated: +1.9 ± 0.1°, $P = .01$, neutral: +0.9 ± 0.2°, $P = .03$; supinated: +0.1 ± 0.3°, $P = .02$). In the injured case, there was no significant effect of forearm rotation on VVA ($P > .05$). However, forearm rotation had a significant effect on IER ($P < .01$), with pronation resulting in more internal rotation that supination (-2.6 ± 0.7°, $P = .03$). Supination most closely replicated the kinematics of the intact elbow.

During active motion, ligament sectioning did not affect VVA or IER ($P > .05$). However, forearm rotation significantly affected VVA in the injured elbow ($P = .005$), with pronation causing significantly increased valgus angle compared to the neutral (+1.2 ± 0.3°, $P = .04$) and supinated (+1.5 ± 0.4°, $P = .03$) positions. There was no effect of forearm rotation on IER in the injured elbow ($P > .09$). There was no difference between active and passive motion in the overhead position for either VVA or IER ($P > .05$).

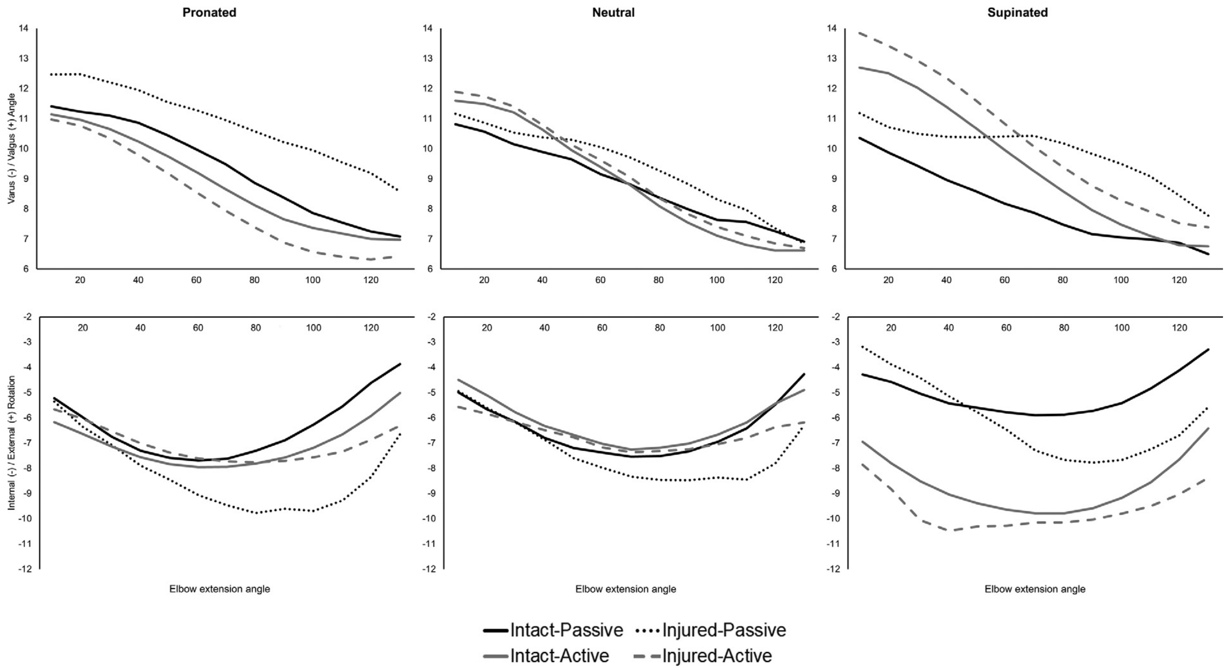

Fig. 4. Mean kinematic profiles with the arm in the overhead position. Varus-valgus angulation (top) and internal-external rotation (bottom) are shown with the forearm in pronation (left), neutral (middle), and supination (right). Four elbow states are shown: intact elbow during passive motion (intact-passive; black, solid); intact elbow during active motion (intact-active; grey, solid); elbow dislocation during passive motion (injured-passive; black, dotted); and elbow dislocation during active motion (injured-active; grey, dashed).

Table 2
Mean varus-valgus angulation (VVA) and ulnohumeral rotation (UHR) ± SD during elbow extension with the arm in the overhead position

			Elbow state			
	Muscle activation	Forearm rotation	Intact	Injured	*P*	*P'*
VVA	Active	Pronated	8.3 ± 7.0°	8.8 ± 6.9°	.25	.005*
		Neutral	8.9 ± 7.7°	9.1 ± 8.2°	.55	
		Supinated	9.5 ± 7.6°	10.3 ± 8.0°	.10	
	Passive	Pronated	9.3 ± 7.3°	10.8 ± 8.8°	.13	.172
		Neutral	8.8 ± 8.1°	9.4 ± 7.2°	.56	
		Supinated	8.1 ± 7.0°	9.9 ± 8.0°	.02*	
UHR	Active	Pronated	-7.0 ± 10.2°	-7.0 ± 10.0°	.98	.09
		Neutral	-6.2 ± 11.6°	-6.6 ± 12.5°	.34	
		Supinated	-8.6 ± 11.1°	-9.6 ± 11.1°	.37	
	Passive	Pronated	-6.4 ± 9.7°	-8.2 ± 9.8°	.01*	<.001*
		Neutral	-6.4 ± 10.5°	-7.3 ± 10.3°	.03*	
		Supinated	-5.1 ± 9.3°	-6.1 ± 9.6°	.02*	

P-values describe the significance of elbow state as the result of a two-way repeated-measures analysis of variance (2WRMANOVA) with elbow state (intact, injured [medial and lateral collateral ligament injury]) and extension angle as variables. *P'*-values describe the significance of forearm rotation in the injured case as the result of a two WRMANOVA with forearm rotation (pronated, neutral, supinated) and extension angle as variables.
* Indicates significance ($P < .05$).

Horizontal position

During passive motion (Fig. 5), there was no significant effect of ligament sectioning on VVA for all forearm positions ($P > .05$, Table 3). With the forearm pronated, internal rotation increased with ligament sectioning (-1.9 ± 0.5°, $P = .004$) but did not change with neutral or supination ($P > .05$). Within the injured elbow condition, there was no significant effect of forearm rotation on VVA or IER ($P > .05$).

During active motion there was no significant effect of ligament sectioning on VVA or IER ($P > .05$). However, in the injured condition, forearm rotation affected VVA ($P = .002$), with supination resulting in a higher valgus angle than pronation (+1.7 ± 0.4°, $P = .02$). No differences in VVA were seen between the other forearm rotations ($P > .05$). In addition, IER was significantly influenced by forearm rotation ($P = .03$). However, post hoc pairwise comparisons elicited no significant differences between forearm rotations ($P > .05$). There was no difference between active and passive motion in the horizontal position for either VVA or IER ($P > .05$).

Arm position effects

During passive motion with the forearm pronated, there was a significant effect of arm position on VVA ($P = .006$). The horizontal position increased varus angulation compared to the dependent position (-4.9 ± 1.4°, $P = .03$). Although the horizontal position increased varus angulation compared to the overhead position, this did not reach statistical significance (-3.8 ± 1.2°, $P = .05$). There were no differences between the overhead and dependent positions ($P > .05$). There was no effect of arm position on VVA when the forearm was neutral or supinated. There was no effect of arm

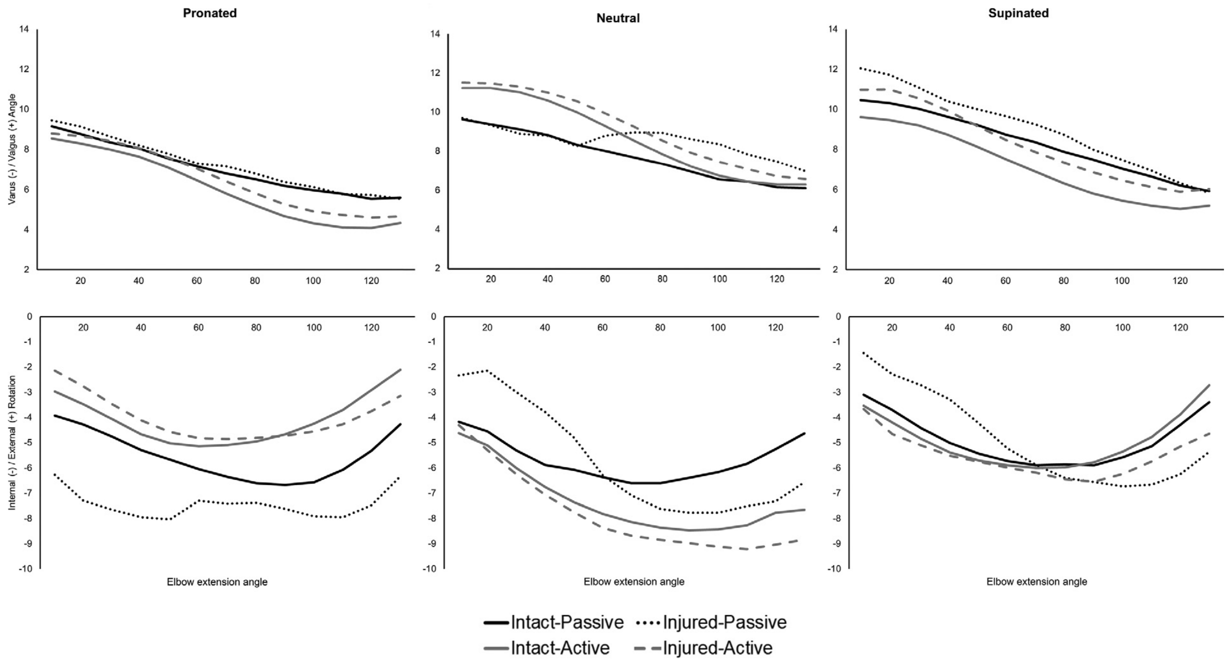

Fig. 5. Mean kinematic profiles with the arm in the horizontal position. Varus-valgus angulation (top) and internal-external rotation (bottom) are shown with the forearm in pronation (left), neutral (middle), and supination (right). Four elbow states are shown: intact elbow during passive motion (intact-passive; black, solid); intact elbow during active motion (intact-active; grey, solid); elbow dislocation during passive motion (injured-passive; black, dotted); and elbow dislocation during active motion (injured-active; grey, dashed).

Table 3
Mean varus-valgus angulation (VVA) and ulnohumeral rotation (UHR) ± SD during elbow extension with the arm in the horizontal position.

			Elbow state			
	Muscle activation	Forearm rotation	Intact	Injured	*P*	*P*'
VVA	Active	Pronated	6.0 ± 6.2°	6.5 ± 5.7°	.44	.002*
		Neutral	8.7 ± 7.5°	9.2 ± 8.1°	.22	
		Supinated	7.1 ± 6.2°	8.2 ± 6.1°	.07	
	Passive	Pronated	7.0 ± 6.1°	7.2 ± 5.8°	.75	.23
		Neutral	7.7 ± 6.7°	8.5 ± 7.1°	.41	
		Supinated	8.3 ± 6.9°	9.0 ± 8.1°	.36	
UHR	Active	Pronated	-4.1 ± 6.1)°	-4.0 ± 6.1°	.80	.03*
		Neutral	-7.0 ± 12.5)°	-7.3 ± 13.2°	.44	
		Supinated	-4.9 ± 6.3)°	-5.5 ± 6.5°	.30	
	Passive	Pronated	-5.5 ± 9.4)°	-7.4 ± 10.1°	.004*	.07
		Neutral	-5.7 ± 10.5)°	-5.7 ± 11.1°	.99	
		Supinated	-4.9 ± 9.9°	-4.8 ± 10.4°	.98	

P-values describe the significance of elbow state as the result of a two-way repeated-measures analysis of variance (2WRMANOVA) with elbow state (intact, injured [medial and lateral collateral ligament injury]) and extension angle as variables. *P*'-values describe the significance of forearm rotation in the injured case as the result of a two WRMANOVA with forearm rotation (pronated, neutral, supinated) and extension angle as variables.
* Indicates significance ($P < .05$).

position on IER when the forearm was pronated. ($P > .05$). However, there was a significant effect of arm position on IER when the forearm was in neutral ($P = .01$) and in supination ($P < .001$). With the forearm neutral, the overhead position increased internal rotation compared to the dependent position (-8.5 ± 2.5°, $P = .04$). There were no other differences between arm positions. When the forearm was supinated, the overhead position increased internal rotation (-12.7 ± 2.2°, $P = .02$) relative to the horizontal position. The dependent position increased external rotation (+11.4 ± 1.8°, $P = .01$) relative to the horizontal position. There was no difference between the dependent and the overhead positions. Across all three arm positions, moving the injured elbow in the overhead position most closely replicated kinematics of the intact elbow during passive motion.

During active motion with the forearm neutral, arm position significantly affected VVA ($P = .02$). The overhead position increased valgus angulation (+0.8 ± 0.2°, $P = .008$) compared to the horizontal position. There were no significant differences between the other arm positions. There was no significant effect of arm position on VVA when the forearm was pronated or supinated ($P > .05$). Arm position did not change IER for any of the forearm positions ($P > .05$). Across all three arm positions, moving the injured elbow in the overhead position most closely replicated kinematics of the intact elbow during active motion.

Discussion

This investigation found that during active motion with the arm overhead, elbow kinematics were not affected by combined MCL-LCL injury. When the arm is overhead, the force of gravity compresses the ulnohumeral articulation.[17] This, combined with the action of the biceps and triceps muscles that cross the articulation, likely explains our findings, as similar results have been found in an investigation of the optimal rehabilitation paradigm of isolated LCL injury.[12] As such, this investigation suggests that patients may be able to perform range-of-motion exercises in the overhead position early in their rehabilitation program in order to prevent elbow stiffness. Elbow stiffness is a common complication of elbow dislocations[24,25] that may result in loss of function as the elbow helps to position the wrist and hand in space for many basic and instrumental activities of daily living.[8] Schreiber and colleagues studied 27 patients following non-operative management of a simple elbow dislocation with overhead motion initiated at 1 week post-injury.[26] At 29 months, patients' mean extension-flexion range was 6° to 137°, and patients did not suffer from instability. This investigation seems to provide a biomechanical basis for that clinical rehabilitation protocol in preventing elbow stiffness.

This investigation showed minimal effect of forearm rotation when the arm was overhead. This is in contrast to previous studies that have shown that forearm rotation impacts varus-valgus elbow laxity after elbow dislocation when the arm is dependent.[27,28] In particular, the benefits of active motion and overhead positioning far outweighed the benefits of forearm rotation in this investigation. After combined collateral ligament injury, the neutral forearm position most closely replicated kinematics of the intact elbow during active extension in the overhead and horizontal positions. In contrast, during passive extension, the pronated position resulted in the injured elbow most closely replicating the IER kinematic pattern of the intact elbow in the dependent position; and forearm supination of the injured elbow most closely replicated the IER kinematic pattern of the intact elbow in the overhead position. The latter had a mean difference of 0.1° from the intact elbow, however, so this is likely not clinically significant. Clinical experience suggests that pronation may be a safer position for the rehabilitation of elbow dislocations, perhaps because dislocations tend to result in more injury to the lateral than the medial elbow.[15,29] This might explain the effect of pronation seen during passive motion in the dependent position. In our study, however, we attempted to section both sides of the elbow equally. Further research on the impact of varying the degree of medial and lateral collateral ligament injury on elbow kinematics would be valuable. In the setting of more medial damage, for example, overhead positioning could potentially result in slightly more gravitational valgus force at the elbow if the humerus is slightly internally rotated or adducted, which might impair ligamentous healing.

This investigation also found that in the elbow with combined MCL-LCL injury, active extension resulted in similar ulnohumeral rotation and varus-valgus angulation patterns to the intact elbow when the arm was in the dependent, overhead, and horizontal positions. The only exception was when the arm was dependent with the forearm in a neutral position. This resulted in increased valgus angulation with active extension. This is in contrast to clinical practice which suggests that if there is equal damage to the medial and lateral stabilizers of the elbow, then neutral positioning should be used in rehabilitation.[7] Outside of this, however, these results agree with previous studies that suggest that active-based exercises are important in the rehabilitation of isolated MCL,[13,30] isolated LCL,[12,14] and combined LCL-MCL injuries.[6] In addition, as kinematics of the injured elbow during passive motion in the dependent position differed from the intact elbow, passive motion in the dependent position should be avoided, at least early in the rehabilitation period, until there has been sufficient healing of both the MCL and LCL.

The simulation of soft tissue injuries presents a limitation to this study, but also represents the worst-case scenario after an elbow dislocation. Clinical studies suggest that after elbow dislocations there is usually high-grade to complete tearing of the MCL structures with intact to complete tears of the LCL structures.[31] In addition, *in vitro* studies cannot reflect other factors such as pain, patient motivation, presence of other injuries as in the case of multiple-trauma, and patient adherence to an exercise prescription and activity restrictions. More female than male specimens were evaluated in this investigation. Amongst adults aged 30-90, females experience more elbow dislocations.[2] Thus our study population was similar to clinical sex distributions. Given our small sample size, we could not evaluate sex effects statistically. Qualitatively, however, there were no sex-based differences in the kinematics of the simulated injury specimens. There was no effect of LCL and MCL injury or muscle activation on elbow kinematics in the overhead position. The study was underpowered to show a difference here, although it was adequately powered to show a difference with the other arm positions. There have been no prior studies of the overhead position in this clinical scenario. Previous investigations using cadaveric studies of elbow dislocations[6,32,33] have used fewer specimens than were used in our study. Given the lack of difference seen in this study, many more specimens than realistically available would be required to look for a minimal, and likely clinically insignificant, effect of muscle activation with the arm overhead.

As mentioned, there may be varying spectra of damage to either collateral ligament in the setting of elbow dislocation. The effect of targeted strengthening of muscles on the side of the more injured collateral ligament (ie, strengthening the wrist flexors that originate at the medial epicondyle in the setting of relatively more MCL than LCL injury) would be an important avenue of future research. In addition, the effect of hinged elbow orthoses on elbow kinematics after elbow dislocation also needs to be studied. These devices are commonly used,[7] but have recently been found to be mechanically ineffective in the setting of isolated LCL[19] and isolated MCL injury.[30]

Conclusions

This investigation demonstrated that active extension exercises in the overhead position should be considered in the rehabilitation of simple elbow dislocations that result in equivalent injury to the MCL and the LCL of the elbow. The effects of forearm rotation in the overhead position were negligible, but neutral forearm rotation seemed to show the closest similarity in kinematic pathways between injured and uninjured elbows with the arm overhead. The beneficial biomechanical effects of muscle activation and gravity in the overhead position on the elbow with combined LCL and MCL injuries may allow for early initiation of active range of motion exercises which may help to reduce elbow stiffness without risking further elbow instability. Passive motion in the dependent position should be avoided early after elbow dislocation.

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References

1. Sheps DM, Hildebrand KA, Boorman RS. Simple dislocations of the elbow: evaluation and treatment. *Hand Clin*. 2004;20:389–404.

2. Stoneback JW, Owens BD, Sykes J, Athwal GS, Pointer L, Wolf JM. Incidence of elbow dislocations in the United States population. *J Bone Jt Surg*. 2012;94:240–245.
3. Josefsson PO, Johnell O, Wendeberg B. Ligamentous injuries in dislocations of the elbow joint. *Clin Orthop Relat Res*. 1987;221:221–225.
4. Bell S. Elbow instability, mechanism and management. *Curr Orthop*. 2008;22:90–103.
5. Hildebrand KA, Patterson SD, King GJW. Acute elbow dislocations: simple and complex. *Orthop Clin North Am*. 1999;30:63–79.
6. Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJW. Rehabilitation of the medial and lateral collateral ligament-deficient elbow: an in vitro biomechanical study. *J Hand Ther*. 2012;25:363–373.
7. Szekeres M, Chinchalkar SJ, King GJW. Optimizing elbow rehabilitation after instability. *Hand Clin*. 2008;24:27–38.
8. Manocha R. Optimizing the rehabilitation of elbow lateral collateral ligament injuries. *Electron Thesis Diss Repos*. 2016. http://ir.lib.uwo.ca/etd/3634.
9. Cohen MS, Hastings H. Acute elbow dislocation: evaluation and management. *J Am Acad Orthop Surg*. 1998;6:15–23.
10. Cyr LM, Ross RG. How controlled stress affects healing tissues. *J Hand Ther*. 1998;11:125–130. doi:10.1016/S0894-1130(98)80009-4.
11. Pipicelli J, Chinchalkar S, Grewal R, Athwal G. Rehabilitation considerations in the management of terrible triad injury to the elbow. *Tech Hand Up Extrem Surg*. 2011;15:198–208.
12. Manocha RHK, Kusins JR, Johnson JA, King GJW. Optimizing the rehabilitation of elbow lateral collateral ligament injuries: a biomechanical study. *J Shoulder Elb Surg*. 2017;26:596–603.
13. Armstrong AD, Dunning CE, Faber KJ, Duck TR, Johnson JA, King GJW. Rehabilitation of the medial collateral ligament-deficient elbow: an in vitro biomechanical study. *J Hand Surg Am*. 2000;25:1051–1057.
14. Dunning CE, Zarzour ZDS, Patterson SD, Johnson JA, King GJW. Muscle forces and pronation stabilize the lateral ligament deficient elbow. *Clin Orthop Relat Res*. 2001;388:118–124.
15. O'Driscoll SW, Morrey BF, Korinek S, An K-N. Elbow subluxation and dislocation: a spectrum of instability. *Clin Orthop Relat Res*. 1992;280:186–197.
16. Schreiber JJ, Warren RF, Hotchkiss RN, Daluiski A. An online video investigation into the mechanism of elbow dislocation. *J Hand Surg Am*. 2013;38:488–494.
17. Lee AT, Schrumpf MA, Choi D, et al. The influence of gravity on the unstable elbow. *J Shoulder Elb Surg*. 2013;22:81–87.
18. Fraser GS, Pichora JE, Ferreira LM, Brownhill JR, Johnson JA, King GJW. Lateral collateral ligament repair restores the initial varus stability of the elbow: an in vitro biomechanical study. *J Orthop Trauma*. 2008;22:615–623.
19. Manocha RH, King GJW, Johnson JA. In vitro kinematic assessment of a hinged elbow orthosis following lateral collateral ligament injury. *J Hand Surg Am*. 2018;43:123–132.
20. Pichora JE, Fraser GS, Ferreira LMF, Brownhill JR, Johnson JA, King GJW. The effect of medial collateral ligament repair tension on elbow joint kinematics and stability. *J Hand Surg Am*. 2007;32:1210–1217.
21. Dunning CE, Gordon KD, King GJW, Johnson JA. Development of a motion-controlled in vitro elbow testing system. *J Orthop Res*. 2003;21:405–411.
22. Ferreira LM, Johnson JA, King GJW. Development of an active elbow flexion simulator to evaluate joint kinematics with the humerus in the horizontal position. *J Biomech*. 2010;43:2114–2119.
23. Johnson JA, Rath DA, Dunning CE, Roth SE, King GJW. Simulation of elbow and forearm motion in vitro using a load controlled testing apparatus. *J Biomech*. 2000;33:635–639.
24. Lansinger O, Karlsson J, Körner L, Måre K. Dislocation of the elbow joint. *Arch Orthop Trauma Surg*. 1984;102:183–186.
25. Mehlhoff TL, Noble PC, Bennett JB, Tullos HS. Simple dislocation of the elbow in the adult: results after closed treatment. *J Bone Jt Surg*. 1988;70:244–249.
26. Schreiber JJ, Paul S, Hotchkiss RN, Daluiski A. Conservative management of elbow dislocations with an overhead motion protocol. *J Hand Surg Am*. 2015;40:515–519.
27. Safran MR, McGarry MH, Shin S, Han S, Lee TQ. Effects of elbow flexion and forearm rotation on valgus laxity of the elbow. *J Bone Jt Surg*. 2005;87:2065–2074.
28. Pomianowski S, O'Driscoll SW, Neale PG, Park MJ, Morrey BF, An KN. The effect of forearm rotation on laxity and stability of the elbow. *Clin Biomech*. 2001;16:401–407.
29. McKee MD, Schemitsch EH, Sala MJ, O'Driscoll SW. The pathoanatomy of lateral ligamentous disruption in complex elbow instability. *J Shoulder Elb Surg*. 2003;12:391–396.
30. Manocha RHK, Johnson JA, King GJW. The effectiveness of a hinged elbow orthosis in medial collateral ligament injuries: an in vitro biomechanical study. *Am J Sports Med*. 2019;47:2827–2835.
31. Schreiber JJ, Potter HG, Warren RF, Hotchkiss RN, Daluiski A. Magnetic resonance imaging findings in acute elbow dislocation: insight into mechanism. *J Hand Surg Am*. 2014;39:199–205. doi:10.1016/j.jhsa.2013.11.031.
32. Søjbjerg JO, Helmig P, Kjaersgaard-Andersen P. Dislocation of the elbow: an experimental study of the ligamentous injuries. *Orthopedics*. 1989;12:461–463.
33. Olsen BS, Henriksen MG, Søjbjerg JO, Helmig P, Sneppen O. Elbow joint instability: a kinematic model. *J Shoulder Elbow Surg*. 1994;3:143–150. doi:10.1016/S1058-2746(09)80093-1.

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1. With active extension
  a. there was no effect on valgus stress
  b. supination increased valgus stress
  c. pronation reduced valgus stress
  d. pronation increased valgus stress

2. PROM is generally withheld until _______ post-op
  a. 4 weeks
  b. 10 weeks
  c. 6 weeks
  d. 8 weeks

3. The target population would be patients who sustain
  a. combined medial and lateral collateral ligament injuries
  b. posterior lateral instability
  c. Fx-dislocation of the distal humerus
  d. LUCL injury

4. Elbow instability was determined at different angles of extension by
  a. neither VVA nor IER
  b. both c and d below
  c. VVA
  d. IER

5. The advantage to performing extension overhead is that it more closely replicates the kinematics of the intact elbow
  a. not true
  b. true

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