Assessment of Forearm Rotational Control Using 4 Upper Extremity Immobilization Constructs

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Abstract

Background: Forearm immobilization techniques are commonly used to manage distal radius, scaphoid, and metacarpal fractures. The purpose of our study was to compare the degree of rotational immobilization provided by a sugar-tong splint (STS), short arm cast (SAC), Munster cast (MC), and long arm cast (LAC) at the level of the distal radioulnar joint (DRUJ), carpus, and metacarpals. **Methods:** Seven cadaveric upper extremity specimens were mounted to a custom jig with the ulnohumeral joint fixated in 90° of flexion. Supination and pronation were unrestricted. K-wires were placed in the distal radius, scaphoid, and metacarpals using fluoroscopic guidance to measure the total arc of rotation referenced to the ulnar ex-fix pin. Baseline measurements followed by sequential immobilization with well-molded STS, SAC, MC, and LAC were obtained with 1.25, 2.5, and 3.75 ft-lb of supination and pronation force directed through the metacarpal K-wire. Each condition was tested 3 times. Digital photographs were taken perpendicular to the ulnar axis to analyze the total arc of motion. **Results:** The most effective constructs from least to greatest allowed rotational arcs were LAC, MC, SAC, and STS. Above-elbow constructs (MC, LAC) demonstrated superior immobilization compared with below-elbow constructs (SAC) ($P < .001$). Circumferential constructs (SAC, MC, LAC) were superior to the noncircumferential construct (STS) ($P < .001$). There were no significant differences between the MC and LAC in all conditions tested. **Conclusions:** Both circumferential and proximally extended immobilization independently improved rotational control of the wrist. However, extending immobilization proximal to the epicondyles did not confer additional stability.

Keywords: forearm rotation, forearm immobilization, radiometacarpal rotation, supination, pronation, wrist rotation

Introduction

Treatment of forearm and carpal injuries often includes immobilization with a splint or cast. Effective immobilization restricts forearm rotation which occurs at the level of the distal radioulnar joint (DRUJ), proximal radioulnar joint (PRUJ), and midcarpal joints.^{7,9,12} Commonly utilized methods of immobilization include a sugar-tong splint (STS), short arm cast (SAC), Munster cast (MC), and long arm cast (LAC). Prior studies have investigated each method of immobilization concluding that the most effective restriction of forearm rotation occurs when immobilization is extended proximal to the level of the elbow.^{13,19} However, many of these studies evaluated rotation at the hand and thus did not measure true forearm rotation. In addition, this comes at the expense of limited elbow motion, which can result in iatrogenic elbow stiffness.^{5,8}

The ideal immobilization construct balances sufficient rigidity to allow healing while imposing the least limitation

to upper extremity function. Immobilizing unaffected joints is avoided to prevent unnecessary stiffness, although this is not always possible when limiting rotational motion. Many activities of daily living involve considerable rotational forces through the wrist, such as turning door knobs, unscrewing lids, or turning a key. Prior studies have reported the arc of pronation and supination at the forearm that can be expected with different immobilization constructs. To our knowledge, no previous study has differentiated the amount of rotational control by immobilization constructs at the level of the DRUJ, carpus, and metacarpals directly.^{13,19}

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Figure 1. External fixator testing setup. External fixator pins were fixed (a) bicortically through the ulna and (b) tricortically through the ulnohumeral joint.

Table 1. The Twelve Testing Conditions.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast
1.25 ft-lb torque	STS 1.25	SAC 1.25	MC 1.25	LAC 1.25
2.5 ft-lb torque	STS 2.5	SAC 2.5	MC 2.5	LAC 2.5
3.75 ft-lb torque	STS 3.75	SAC 3.75	MC 3.75	LAC 3.75

Note. STS = sugar-tong splint; SAC = short arm cast; MC = Munster cast; LAC = long arm cast.

The purpose of this study was to investigate the rotational control provided by each method of immobilization (STS, SAC, MC, LAC) and to assess the effect of varying loads on rotational control. We further sought to evaluate the extent of rotational control provided by each immobilization construct at the level of the DRUJ, carpus, and metacarpals by utilizing a cadaveric model. We hypothesized that rotational control improves with circumferential immobilization and with proximal extension of the immobilization.

Materials and Methods

Specimen Preparation

Eight fresh-frozen cadaveric upper extremity specimens (4 matched pairs) were utilized in this investigation. Specimens were screened prior to acquisition, and specimens from donors with upper extremity trauma or previous surgery were excluded. Six specimens were obtained from male donors, and 2 specimens were obtained from a female donor. Mean age at the time of death was 79.8 years (range, 66-94 years). Specimen preparation and testing were performed in the Bioskills laboratory at our institution.

Specimens were thawed at room temperature 12 hours prior to testing. Specimens were then fixed to a table-mounted external-fixator system, rigidly stabilizing the

ulna. The ulnohumeral joint was immobilized in 90° of flexion by transfixing the proximal external fixator pin from the ulna to the distal humerus with tricortical pin purchase (Figures 1a and 1b). External fixator pin placement was performed with allowance of unrestricted rotation of the radius around the ulna. Next, a 1.6-mm K-wire was placed in the distal radius at the level of the DRUJ unicortically, a 1.6-mm K-wire was placed in the scaphoid unicortically, and a 2.0-mm K-wire was placed in the second through fifth metacarpal necks in a plane parallel to the radial shaft (zero-rotation). A larger diameter K-wire was used for metacarpal fixation as this would be the site of construct loading. All pin fixations were performed under fluoroscopic guidance. Upon fluoroscopic inspection, a single specimen was noted to have sustained an ulna fracture while placing the external fixator pin and was excluded from testing and data analysis.

Testing Protocol

Four immobilization conditions (STS, SAC, MC, LAC) and 3 deforming torque conditions (1.25, 2.5, and 3.75 ft-lb) were assessed in this investigation for a total of 12 unique testing conditions (Table 1). Each cast and splint was placed by one of two authors with the application of an interosseous

mold. Two rolls of 4-inch plaster in the standard 10 layers overwrapped with elastic bandage were used to fashion STS. One roll of 4-inch fiberglass tape was used for the SAC, with an additional roll of 4-inch fiberglass tape used to extend to an MC, and a final roll of 4-inch fiberglass tape used to extend to an LAC. Drying time was approximately 20 minutes for each splint and 10 minutes each time casting or extension of the cast was performed according to manufacturer instructions. All splinting and casting were performed around the external fixator pins and K-wires with no areas of the casts impeding K-wire motion.

Each testing condition was loaded with 1.25, 2.5, and 3.75 ft-lb of torque in pronation and supination. Sequentially, 5 lb, 10 lb, and 15 lb weights were secured to the metacarpal K-wire 6 inches from the axis of rotation (ulna) and at a 30° angle to gravity. As $\text{Torque} = \text{radius (in feet)} \times \text{weight (in pounds)} \times \sin\theta$, the resultant deforming torque was calculated to be 1.25, 2.5, and 3.75 ft-lb. A standardized camera system was used to obtain a digital photograph taken 4 feet away from the testing jig to determine the pronation-supination arc for each testing condition. The photographs were obtained en-face along the axis of the ulna with the ulnar external fixator pins as well as distal radius, scaphoid, and metacarpal K-wires clearly visible (Figure 2). The photographs were analyzed with an imaging program ImageJ (National Institutes of Health; Bethesda, Maryland) to measure resultant pronation and supination motion for each for testing condition. ImageJ has been used in several orthopedic investigations as a means of calibrated quantification of angles, distance, and area.^{2,6,16} The pronation and supination displacement for each condition was calculated by measuring the angle between the distal most ulnar external fixator pin and the appropriate measurement K-wire when the arm was loaded in pronation and supination, respectively. The total pronation-supination arc was calculated as the sum of the pronation and supination angles for a particular testing condition at the DRUJ (distal radius K-wire), carpus (scaphoid K-wire), and metacarpals (metacarpal neck K-wire). Each testing condition was performed 3 times with each individual pronation and supination measurement obtained and recorded via digital photography.

Statistical Analysis

Pronation and supination data were recorded on a computer spreadsheet. Total pronation-supination arcs were averaged for each testing condition. Normality tests revealed nonnormally distributed data, and Kruskal-Wallis and Mann Whitney *U* tests were used to analyze nonparametric continuous data. All statistical analyses were performed using JMP Pro 10 Software (SAS Institute, Inc; Cary, North Carolina). A *P* value < .05 was considered significant.

Figure 2. Example of a digital image “en face” axial view of a cadaveric specimen mounted to external fixator jig with long arm cast in place and torque applied in supination.

Note. Rotational analysis was performed using ImageJ software system to measure E-R, E-S, and E-M in pronation and supination. The absolute difference in angles between supination and pronation constituted the total arc of motion. E, external fixator pin axis; R, distal radius pin; S, scaphoid pin; M, metacarpal pin; θ , angle used in torque measurement (30°).

Results

Total Arc of Motion Under 1.25 ft-lb of Deforming Torque

Significant differences in rotation among the immobilization constructs were found at the DRUJ ($P < .001$), carpus ($P < .001$), and metacarpals ($P < .001$). Significant differences in rotation were also found among the level of

Table 2. Total Arc of Motion Allowed by Immobilization Constructs Under 1.25 ft-lb of Deforming Torque.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast	P value
DRUJ	21.2 ^{o†‡}	17 ^{o§}	4.3 ^{o†§}	2.8 ^{o‡}	<.001
Midcarpal	30.6 ^{o†‡}	19.9 ^{o§}	7.7 ^{o†§}	5 ^{o‡}	<.001
Metacarpal	43.9 ^{o†‡§}	27.2 ^{o†}	17.8 ^{o‡}	18.8 ^{o§}	<.001

Note. Pairwise comparison among constructs at the DRUJ: [†]STS vs MC; $P < .001$, [‡]STS vs LAC; $P < .001$, [§]SAC vs MC; $P = .001$, ^{||}SAC vs LAC; $P < .001$. Pairwise comparison among constructs at the carpus: [†]STS vs MC; $P < .001$, [‡]STS vs LAC; $P < .001$, [§]SAC vs MC; $P = .008$, ^{||}SAC vs LAC; $P < .001$. Pairwise comparison among constructs at the metacarpals: [†]STS vs SAC; $P = .008$, [‡]STS vs MC; $P < .001$, [§]STS vs LAC; $P < .001$. DRUJ = distal radioulnar joint; STS = sugar-tong splint; MC = Munster cast; LAC = long arm cast; SAC = short arm cast.

Table 3. Total Arc of Motion Allowed by Immobilization Constructs Under 1.25 ft-lb of Deforming Torque.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast
DRUJ	21.2 ^{o†}	17 ^{o†}	4.3 ^{o†}	2.8 ^{o†}
Midcarpal	30.6 ^{o‡}	19.9 ^o	7.7 ^{o‡}	5 ^{o‡}
Metacarpal	43.9 ^{o†‡}	27.2 ^{o†}	17.8 ^{o†‡}	18.8 ^{o†‡}
P value	.001	.089	<.001	<.001

Note. Pairwise comparison among anatomic levels in STS: [†]metacarpal vs DRUJ; $P = .003$, [‡]metacarpal vs midcarpal; $P < .001$. Pairwise comparison among anatomic levels in SAC: [†]metacarpal vs DRUJ; $P = .03$. Pairwise comparison among anatomic levels in MC: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P < .001$. Pairwise comparison among anatomic levels in LAC: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P < .001$. DRUJ = distal radioulnar joint; STS = sugar-tong splint; SAC = short arm cast; MC = Munster cast; LAC = long arm cast.

Table 4. Total Arc of Motion Allowed by Immobilization Constructs Under 2.5 ft-lb of Deforming Torque.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast	P value
DRUJ	38 ^{o†‡}	27.9 ^{o§}	5.4 ^{o†§}	3.8 ^{o‡}	<.001
Midcarpal	53.4 ^{o†‡§}	32.2 ^{o† φ}	10.3 ^{o‡}	8.5 ^{o§φ}	<.001
Metacarpal	72.9 ^{o†‡§}	45.3 ^{o† φ}	26.4 ^{o‡}	25.6 ^{o§φ}	<.001

Note. Pairwise comparison among constructs at the DRUJ: [†]STS vs MC; $P < .001$, [‡]STS vs LAC; $P < .001$, [§]SAC vs MC; $P < .001$, ^{||}SAC vs LAC; $P < .001$. Pairwise comparison among constructs at the carpus: [†]STS vs SAC; $P = .007$, [‡]STS vs MC; $P < .001$, [§]STS vs LAC; $P < .001$, ^{||}SAC vs MC; $P < .001$, ^φSAC vs LAC; $P < .001$. Pairwise comparison among constructs at the metacarpals: [†]STS vs SAC; $P = .001$, [‡]STS vs MC; $P < .001$, [§]STS vs LAC; $P < .001$, ^{||}SAC vs MC; $P = .007$, ^φSAC vs LAC; $P = .006$. DRUJ, distal radioulnar joint; STS = sugar-tong splint; MC = Munster cast; LAC = long arm cast; SAC = short arm cast.

immobilization for STS ($P < .001$), MC ($P < .001$), and LAC ($P < .001$). Tables 2 and 3 highlight the statistically significant pairwise differences among the immobilization constructs and among the level of immobilization, respectively.

Total Arc of Motion Under 2.5 ft-lb of Deforming Torque

Significant differences in rotation among the immobilization constructs were found at the DRUJ ($P < .001$), carpus ($P < .001$), and metacarpals ($P < .001$). Significant differences in rotation were also found among the level of immobilization for STS ($P < .001$), SAC, ($P = .027$), MC ($P < .001$), and LAC ($P < .001$). Tables 4 and 5 highlight the statistically significant pairwise differences among the immobilization constructs and among the level of immobilization, respectively.

Total Arc of Motion Under 3.75 ft-lb of Deforming Torque

Significant differences in rotation among the immobilization constructs were found at the DRUJ ($P < .001$), carpus ($P < .001$), and metacarpals ($P < .001$). Significant differences in rotation were also found among the level of immobilization for STS ($P < .001$), SAC, ($P = .017$), MC ($P < .001$), and LAC ($P < .001$). Tables 6 and 7 highlight the statistically significant pairwise differences among the immobilization constructs and among the level of immobilization, respectively.

Discussion

Rotational motion is described primarily at the forearm and PRUJ; however, a significant amount of axial rotation occurs at the wrist. Rotational motion of the wrist occurs at

Table 5. Total Arc of Motion Allowed by Immobilization Constructs Under 2.5 ft-lb of Deforming Torque.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast
DRUJ	38° [†]	27.9° [†]	5.4° ^{†‡§}	3.8° ^{†§}
Midcarpal	53.4° [‡]	32.2° [‡]	10.3° ^{‡§}	8.5° ^{‡§}
Metacarpal	72.9° ^{†‡}	45.3° ^{†‡}	26.4° ^{†‡}	25.6° ^{†‡}
P value	<.001	.027	<.001	<.001

Note. Pairwise comparison among anatomic levels in STS: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P = .031$. Pairwise comparison among anatomic levels in SAC: [†]metacarpal vs DRUJ; $P = .016$, [‡]metacarpal vs midcarpal; $P = .036$. Pairwise comparison among anatomic levels in MC: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P < .001$, [§]midcarpal vs DRUJ; $P = .005$. Pairwise comparison among anatomic levels in LAC: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P < .001$, [§]midcarpal vs DRUJ; $P = .002$. DRUJ = distal radioulnar joint; STS = sugar-tong splint; SAC = short arm cast; MC = Munster cast; LAC = long arm cast.

Table 6. Total Arc of Motion Allowed by Immobilization Constructs Under 3.75 ft-lb of Deforming Torque.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast	P value
DRUJ	54.2° ^{†‡§}	38.8° ^{†‡}	6.2° ^{†‡‡§}	4.2° ^{§‡}	<.001
Midcarpal	74.8° ^{†‡§}	47.4° ^{†‡}	14.3° ^{†‡‡§}	13.7° ^{§‡}	<.001
Metacarpal	100.3° ^{†‡§}	65.2° ^{†‡}	32.4° ^{†‡‡§}	32° ^{§‡}	<.001

Note. Pairwise comparison among constructs at the DRUJ: [†]STS vs SAC; $P = .045$, [‡]STS vs MC; $P < .001$, [§]STS vs LAC; $P < .001$, ^{||}SAC vs MC; $P < .001$, [¶]SAC vs LAC; $P < .001$. Pairwise comparison among constructs at the carpus: [†]STS vs SAC; $P = .024$, [‡]STS vs MC; $P < .001$, [§]STS vs LAC; $P < .001$, ^{||}SAC vs MC; $P < .001$, [¶]SAC vs LAC; $P < .001$. Pairwise comparison among constructs at the metacarpals: [†]STS vs SAC; $P = .002$, [‡]STS vs MC; $P < .001$, [§]STS vs LAC; $P < .001$, ^{||}SAC vs MC; $P < .001$, [¶]SAC vs LAC; $P < .001$. DRUJ = distal radioulnar joint; STS = sugar-tong splint; SAC = short arm cast; MC = Munster cast; LAC = long arm cast.

Table 7. Total Arc of Motion Allowed by Immobilization Constructs Under 3.75 ft-lb of Deforming Torque.

	Sugar-tong splint	Short arm cast	Munster cast	Long arm cast
DRUJ	54.2° [†]	38.8° [†]	6.2° ^{†§}	4.2° ^{†§}
Midcarpal	74.8° [‡]	47.4° [‡]	14.3° ^{‡§}	13.7° ^{‡§}
Metacarpal	100.3° ^{†‡}	65.2° ^{†‡}	32.4° ^{†‡}	32° ^{†‡}
P value	<.001	.017	<.001	<.001

Note. Pairwise comparison among anatomic levels in STS: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P = .017$. Pairwise comparison among anatomic levels in SAC: [†]metacarpal vs DRUJ; $P = .007$, [‡]metacarpal vs midcarpal; $P = .049$. Pairwise comparison among anatomic levels in MC: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P = .002$, [§]midcarpal vs DRUJ; $P = .001$. Pairwise comparison among anatomic levels in LAC: [†]metacarpal vs DRUJ; $P < .001$, [‡]metacarpal vs midcarpal; $P < .001$, [§]midcarpal vs DRUJ; $P < .001$. DRUJ = distal radioulnar joint; STS = sugar-tong splint; SAC = short arm cast; MC = Munster cast; LAC = long arm cast.

several levels including the DRUJ, radiocarpal, and midcarpal joints. Several studies have examined wrist rotation in terms of radiometacarpal motion, which combines rotation at both the radiocarpal and the midcarpal joints.^{10,15} Gupta et al further examined the radiocarpal and midcarpal joints separately, demonstrating an average of 17° of combined radiometacarpal rotation with the vast majority of that motion occurring at the midcarpal joint.³ Wrist motion, including flexion and extension as well as radial and ulnar deviation, demonstrates a small amount of axial rotation during these movements.^{4,17,20,21}

Restriction of rotational motion has been shown to have great importance in the treatment of wrist injuries due to the effects of pronation and supination on the biomechanical stability of the wrist.²² Most injuries of the wrist, including distal radius fractures, DRUJ injuries, and scaphoid fractures,

demonstrate effective healing when immobilized for a period of weeks to months.^{1,14,18} We chose to test 4 common methods of immobilization of the wrist while comparing motion at 3 levels of wrist rotation.

Our results demonstrate several distinct patterns. The most effective immobilization techniques in order of most to least rotational control were LAC, MC, SAC, and STS. The above-elbow constructs (MC and LAC) demonstrated superior immobilization compared with below-elbow construct (STS and SAC) under all deforming torques (1.25, 2.5, and 3.75 ft-lb) at all anatomic locations (DRUJ, carpus, and metacarpals). The LAC demonstrated no statistically significant superiority to MC in any of the testing conditions. Our results indicate that MC provides similar rotational control to an LAC in regard to stability of the wrist, which may be of benefit in cases where allowance of elbow flexion and

extension is of prime importance. The circumferential constructs (SAC, MC, and LAC) all demonstrated superior immobilization compared with the noncircumferential construct (STS) in all conditions tested. The least restrictive circumferential immobilization technique was the SAC while the most restrictive was the LAC. Circumferential immobilization demonstrated increasing benefit at higher loads.

Circumferential immobilization additionally demonstrated superior rotational control at more distal anatomic locations where rotational arcs were greatest. At the metacarpals, all 3 test loads demonstrated a significantly greater rotational arc allowed by the STS compared with all 3 circumferential constructs. At the scaphoid, the 2.5 and 3.75 ft-lb deforming torque loads demonstrated the same pattern, while 3.75 ft-lb of deforming torque applied at the DRUJ demonstrated the same pattern. As expected by extrapolation, each immobilization construct under each loading condition demonstrated increased rotational control at the more proximal level of the DRUJ compared with the level of the metacarpal. However, only MC and LAC under 2.5 and 3.75 ft-lb of deforming torque demonstrated significant differences when comparing in rotational control at the level of the carpus and metacarpals. We conclude that circumferential immobilization provides superior rotational control, especially at higher loads and at more distal joints for which rotational stresses are expected to be greater.

Interestingly, SAC provided no significant improvement in rotational control over STS at the DRUJ under 1.25 and 2.5 ft-lb of deforming torque. Similarly, there was no significant difference in rotational control for SAC and STS constructs at the carpus under 1.25 ft-lb of deforming torque; however, SAC provided superior immobilization under 2.5 and 3.75 ft-lb of deforming torque. Thus, STS may offer similar rotational control to SAC at the DRUJ and carpus, provided patients are strictly adherent to weight restriction instructions.

Kim et al performed a comparison of forearm pronation and supination permitted by short arm splints, SACs, STSs, long arm splints, and LACs in 40 healthy volunteers.¹¹ They found that the LAC decreased rotational motion to less than 10% of baseline, while all the other immobilization techniques reduced immobilization to within 40% of baseline. They found no significant difference between the SAC, STS, and long arm splint. However, this study measured "forearm rotation" at the metacarpal level of a gripped hand, and thus includes carpal rotation and motion at the carpometacarpal joints.

Trocchia et al evaluated forearm pronation and supination in 15 healthy volunteers using an LAC, MC, removable splint at 90° of elbow flexion, and a splint allowing elbow flexion similar to the MC.¹⁹ They found the LAC to provide the greatest degree of elbow immobility, while the MC offered a similar restriction of the pronosupination arc but still allowing flexion-extension of the elbow. They

recommended the MC as a reasonable option for limiting forearm rotation without completely immobilizing the elbow. Similarly, our results demonstrated a significant difference in rotation at these levels under nearly all test conditions. However, the study by Trocchia et al was limited by the inability to differentiate rotational motion occurring at the carpus versus the forearm.

This current study has several limitations. Our testing construct relied on loading the metacarpal pin to create a torque moment about the ulna. Given the relatively high loads applied, there was the potential for bending or pullout during loading. For this reason, slightly larger diameter K-wires were used and fixed across 4 metacarpals with at least 7 cortices of fixation confirmed by fluoroscopy. In addition, the loading was applied to the K-wire at a relatively short distance from the skin interface, minimizing torquing forces on the pin that could affect angle measurements. In our study, there was no evidence of K-wire pullout or deformation during testing. The authors applying the casts and splints were not blinded to the study, which may introduce the potential for biased application of immobilization constructs. However, all splint and cast constructs were applied utilizing a standard protocol at our institution to minimize this bias including number of layers of fiberglass and plaster, drying time, level of proximal extension of each construct, and utilization of interosseous mold. Utilization of a cadaveric model excludes the ability to evaluate clinical factors such as active maximal effort or dynamic sources of rotation. However, our cadaveric model provided the unique opportunity to delineate motion at multiple levels of the wrist as opposed to combined radiocarpal-metacarpal motion. The immobilization constructs were applied around the transfixed ulnar pins, which has the potential to weak the constructs at the 2 locations of the ulnar pins. While the pins did not interfere with the STS, they did require modification of the SAC, MC, and LAC constructs in which the fiberglass was wrapped around the pin sites. This may have altered the biomechanics of the cast similar to creating a small window; however, given that the pins were partially overwrapped with the fiberglass and essentially incorporated into the cast construct, we believe this effect was minimal. Last, the use of digital photography and advanced imaging software for angular measurement may be subject to observational error. However, previous literature using digital measurement software has shown minimal observer bias with this technique.^{2,6,16} In addition, all trials were conducted in 1 sitting with the digital camera placed in a standardized position directly perpendicular to the axis of the ulna for all photographs. We believe this mitigated the majority of observational error that could occur with positional changes and therefore measurement errors in-between taking photographs.

In summary, both circumferential and proximally extended immobilization constructs independently provide

improved rotational control of the wrist. Circumferential immobilization extending proximal to the elbow provided the greatest rotational control at the DRUJ. Similar rotational control at the forearm can be obtained with an MC as compared with an LAC, thus allowing the extremity some degree of flexion-extension motion. Well molded below-elbow constructs may be a reasonable alternative for carpal injuries in lower demand patients and in other injuries that do not require as extensive a limitation in forearm rotation.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

This article does not contain any studies with human or animal subjects.

Statement of Informed Consent

This article does not contain any studies with human or animal subjects.

Declaration of Conflicting Interests

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