SCIENTIFIC ARTICLE

The Effect of Forearm Shortening on Forearm Range of Motion

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Purpose Osseous shortening of the forearm is performed during forearm replantation; however, no large clinical reviews have discussed its effects on patient outcomes. A recent cadaver study demonstrated the progressive loss of forearm pronation/supination ranges of motion with increased shortening lengths using external fixation. Our study aimed to quantify the effects of shortening on passive forearm motion using internal fixation after 2, 4, and 6 cm of mid-forearm shortening.

Methods A volar Henry approach and direct approach to the ulna were used on 8 cadaveric specimens. The forearms were sequentially shortened by 2, 4, and 6 cm. Fixation was performed on the volar surfaces of the radius and ulna. Pronation and supination of the forearms were tested by applying 1 Nm of torque at baseline and after the fixation of both the radius and ulna using osteotomy. Radiographs and measurements were obtained at each phase to determine the maximum radial bow and radioulnar gap. Data were analyzed using a linear mixed-effects model.

Results Greater shortening of the radius and ulna led to progressively greater reductions in both pronation and supination range of motion. Larger differences were seen in supination at 2–4 cm of shortening and in pronation at 4–6 cm of shortening. Changes in supination were found to be associated with the radial bow and radioulnar gap; changes in pronation were found to be associated with the radial bow and radial bow's location.

Conclusions This study demonstrates that quantifiable effects on passive forearm motion occur after osseous shortening of the forearm.

Clinical relevance This information may improve surgeons' and patients' understanding of the changes in forearm motion expected after shortening in the setting of replantation or tumor resection or in the setting of limb salvage of a mangled extremity. *(J Hand Surg Am. 2022;47(1):87.e1-e7. Copyright © 2022 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Biomechanical models, forearm biomechanics, forearm shortening, pronation, supination.

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In the upper extremity, the forearm provides a stable platform for the hand and wrist while permitting the supination and pronation required for personal care and interaction with the environment. The importance of the forearm has been demonstrated by the profound impact that complex injuries and amputations may have on a patient's function.[1,2] Over the past few decades, advances in

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surgical and reconstructive techniques have permitted the replantation of forearm-level amputations, and several studies have reported positive results following replantation.[1,3,4] In the setting of forearm amputations, bony shortening may be critical to success.[5] Malt and McKhann[6] discussed skeletal stabilization as a foundation for neurovascular anastomosis and recommended 2−3 inches of bony shortening to allow a tension-free repair. Osseous shortening may also be required as a result of tumor resection and reconstruction.[7,8] Despite improvements in techniques and outcomes, the paucity of cases reported in the literature means that certain technical aspects of upper-extremity replantation are based on limited evidence. In particular, the effect of osseous shortening on functional outcomes has not been well described.

Previous studies have addressed the isolated shortening of the radius or ulna, which has been shown to affect the distal radioulnar joint, triangular fibrocartilage complex, and interosseous membrane.[9] In addition, the effect of malunions and nonunions on rotational and axial stability of the forearm has been described, with the loss of the radial bow, in particular, limiting rotation of the forearm.[8] Recently, a cadaveric study evaluated the effects of simultaneous shortening of the radius and ulna using an external fixator system. The study tested the effects of 1−5 cm of shortening in the proximal, middle, and distal thirds of the forearm. Although the authors noted a loss of forearm rotation after shortening of the forearm in the middle and distal thirds, the limitations of the study included the use of only 3 specimens in each group and the inherent instability associated with external fixation systems.[10] To our knowledge, the effect of forearm shortening on the range of motion using an internal fixation construct has not been studied in a cadaveric model. Therefore, the aim of this study was to examine the effects of osseous shortening using internal fixation on forearm range of motion using a cadaveric model.

MATERIALS AND METHODS

Specimens

Institutional Biosafety Committee approval at the University of Washington was obtained prior to commencing this study. Eight cadaveric right-arm specimens, partitioned at the mid-humerus level, from 5 male and 3 female donors with a mean age of 56.7 years (range 48−83 years) and mean body mass of 73.6 kg (range 54.1−93.6 kg) were included as a sample of convenience. The specimens had not undergone previous forearm surgery and were evaluated radiographically to confirm the absence of deformity or arthritis prior to use. The specimens were stored at −19 °C until required for testing; then, they were thawed at room temperature.

The humerus was cut 20 cm proximal to the elbow joint. The soft tissue was removed from the proximal end of the humerus, and the bone was embedded in polymethylmethacrylate. Two screws (3-mm diameter × 100-mm length) were inserted bicortically and in parallel (30 mm apart) into the radial aspect of the distal radius to permit an accurate assessment of the rotational axis of the forearm. Additional screws were inserted into the distal aspect of the radius and ulna to allow the attachment of motion-capture marker clusters. A volar Henry approach and direct approach to the ulna were used to access the bones of the forearm.[11]

Study procedures

A robotic testing system consisting of a 6-degree-of-freedom hexapod (model R2000; Mikrolar) and an additional flexion fixture (Newmark Systems, Inc) that provides a range of motion of up to 120° of elbow flexion were used for this study. The system can be operated in a force or motion-control mode. This experiment used force control; this mode takes feedback from a load cell (Theta IP65; ATI Industrial Automation) to control the position of the arm until the desired loading condition is achieved. A motion-capture system (Polaris; Northern Digital Inc) was used to track the movement of individual bones using the marker clusters.

The prepared specimens were mounted on the robotic testing system, with the forearm oriented vertically and the elbow flexed to 90° (Fig. 1). The humerus was attached to the flexion fixture via a 6.35-cm diameter collar clamped to a cement pot, and the long screws attached to the radius were clamped securely to a custom fixture connected directly to the load cell. A joint coordinate system was defined using a 6-degree-of-freedom spatial digitizer (Model G2LX; eMicroScribe) by marking the long axes of the humerus and forearm along with the medial and lateral epicondyles of the elbow.

A previous study by Chuang et al[12] classified traction avulsion injuries of the forearm based on their level, location relative to the musculotendinous unit, and neurologic supply. Chuang et al[12] noted that majority of these injuries occurred within the mid forearm at the level of the muscle belly, distal to the neuromuscular junction. Therefore, the middle third of the forearm was chosen as the site of shortening in

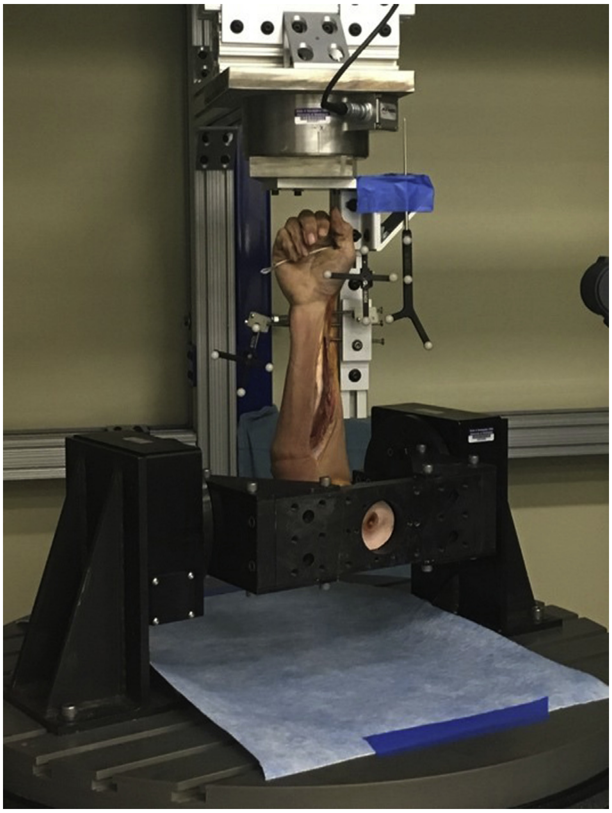

FIGURE 1: Specimen mounted on a robotic testing system.

the current study. The total length of the ulna was measured using a metallic ruler, and the forearm was divided into 3 parts. The distal aspect of the middle third of the ulna was marked along with the corresponding point on the radius and measured from the radial styloid. Additional marks were made 2, 4, and 6 cm proximal to the middle- and distal-third junction in order to plan the corresponding shortening osteotomies.

After preconditioning, internal and external torques were applied to the arm. The torques were linearly ramped from 0 Nm to 1 Nm over 10 seconds and held at 1 Nm for an additional 10 seconds before being linearly ramped back to 0 Nm. This loading cycle was repeated 10 times for supination and pronation. During testing, position and force measurements were sampled at 20 Hz. Preliminary testing showed that 1 Nm allowed an approximately full range of motion of the forearm without causing loosening of the experimental and surgical hardware. The specimens were initially tested while they were intact. Testing was then repeated after 3 different levels of forearm shortening: 2, 4, and 6 cm. To shorten the forearm, transverse osteotomies of the radius and ulna were performed using a microsagittal saw, and a 2-cm segment of the bones were removed.

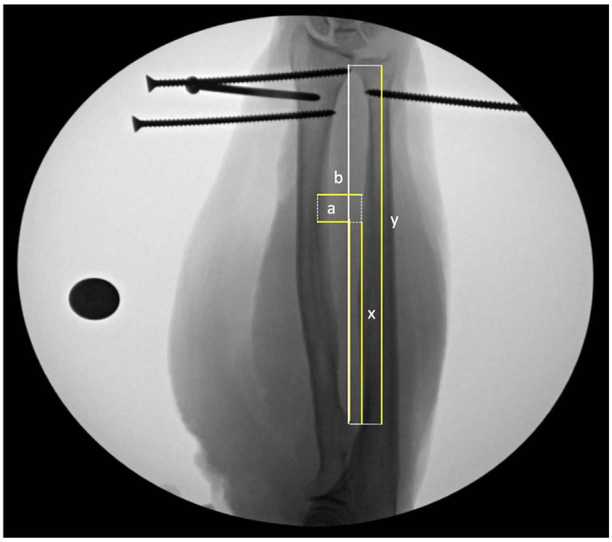

FIGURE 2: Representative radiographic specimen demonstrating the key anatomical landmarks that were obtained at baseline and under each condition. a Maximum radial bow (mm). b Radioulnar gap (mm); radial bow location (%): $\frac{x}{y} \times 100$.

After each osteotomy, direct apposition between the proximal and distal aspects of the radius and ulna was achieved, and the bones were stabilized using 3.5-mm limited-contact dynamic compression plates (Synthes Inc) placed on the volar surfaces of the radius and ulna. For each test condition, an x-ray of the anteroposterior aspect was also performed.

Data analysis

The rotational position of the arm was determined at 0.5 Nm, 0.75 Nm, and 1.0 Nm of loading across the final 5 cycles in each direction, and the mean rotation of the arm was determined for supination and pronation. Key anatomic landmarks were digitized on the arm x-rays and obtained for each condition (baseline as well as 2, 4, and 6 cm of shortening). The following landmarks were included: (1) radial bow, defined as the point on the ulnar aspect of the radial shaft farthest perpendicularly (Fig. 2A) from a line drawn between the ulnar cortex of the distal radius and bicipital tuberosity; (2) radiaoulnar gap (Fig. 2B), defined as the distance between the radius and ulna at the point of maximal radial bow; and (3) location of the maximum radial bow, defined as distance "x," which is the vertical distance between the bicipital tuberosity and the point of maximal radial bow, divided by the total vertical distance between the bicipital tuberosity and the most ulnar aspect of the distal radius "y," expressed as a percentage (%): $\frac{x}{y} \times 100$ (Fig. 2)[12-14] Linear mixed-effects regression was used to determine if pronation, supination, and

TABLE 1. Changes in the Range of Motion as a Result of Forearm Shortening With 1 Nm Moments Applied

Conditions	Estimated Difference, Degrees (*P* Value, [95% CI])	
	Pronation	Supination
Intact versus 2 cm	−5.8 (.03, [−11.2 to −0.5])*	−8 (.08, [−21 to 0.5])
Intact versus 4 cm	−8.6 (<.001, [−14 to −3.3])*	−21.1 (<.001, [−28.8 to −13.4])]*
Intact versus 6 cm	−18.2 (<.001, [−23.6 to −12.8])*	−24.7 (<.001, [−32.4 to −17.0])*
2 cm versus 4 cm	−2.8 (.52, [2.4 to −8.1])	−13.9 (<.001 [−21.6 to −6.2])*
2 cm versus 6 cm	−12.4 (<.001, [−17.7 to −7.0])*	−17.5 (<.001, [−25.2 to −9.8])*
4 cm versus 6 cm	−9.6 (<.001, [−14.9 to −4.3])*	−3.6 (.63, [−11.3 to 4.1])

*Statistically significant changes ($P < .05$).

anatomical variables changed after shortening. Linear mixed models are particularly useful in a repeated-measure design like this because they take into account the lack of independence between observations within the same forearm in different shortening conditions.[15] The degree of forearm rotation and anatomical variables were modeled as dependent variables, the surgical condition as fixed effect, and specimen and specimen-condition interactions as random. If a significant association was found, pairwise comparisons were performed using the Tukey's range test to correct for multiple comparisons. In order to control for variations in arm length among the specimens, changes in pronation and supination were also evaluated based on the amount of shortening, expressed as a percentage of the initial arm length.

RESULTS

Changes in pronation and supination ranges of motion are summarized in Table 1. It was found that both pronation and supination were significantly affected when the intact condition was compared with that of 6 cm of shortening ($P < .05$). Increasing the amount of shortening led to progressively greater reductions in the range of motion (Fig. 3). A significant association was also determined between the percentage of reduction of arm length and both pronation ($P < .05$) and supination ($P < .05$) (Fig. 4).

The radial bow, radioulnar gap, and location of the maximum radial bow were found to be significantly affected by shortening ($P < .05$). The differences between the shortening conditions are presented in Table 2 (Fig. 5A−D).

Supination of the arms across the conditions was found to be associated with the radial bow ($R^2 = 0.26$, $P < .05$) and radioulnar gap ($R^2 = 0.20$, $P < .05$). Pronation was found to be associated with the radial bow ($R^2 = 0.28$, $P < .05$) and radial bow's location ($R^2 = 0.27$, $P < .05$).

DISCUSSION

The forearm has been termed as a "functional" joint because of its ability to pronate and supinate the hand in space.[14] Although forearm replantations have been performed for more than 50 years,[13] there are less quantitative data regarding the effects of forearm shortening on supination or pronation. Compared with previously published studies,[10] we used internal fixation techniques combined with sequential shortening in the middle third of the forearm to evaluate the effects of shortening on forearm range of motion.

We focused on a single region, the middle third of the forearm, which is commonly involved in forearm replantation.[12] The soft-tissue envelope of the elbow, forearm, and wrist was maintained in our study testing the range of motion. Our study included 8 specimens per condition compared with a previous study that used 3 specimens per condition. Most importantly, our specimens were tested under each condition while carefully controlling the force applied (up to 1 Nm) to the specimens to ensure that equal and replicable torques were applied to each forearm. This feature of our study allowed for highly accurate and comparable supination and pronation measurements.

Previous articles have documented the effects of malunions and nonunions on forearm supination and pronation.[8,16,17] We demonstrated that pronation and supination decreased as the magnitude of shortening was increased; however, compared with prior studies,[10] our results did not show a linear relationship between the loss of forearm range of motion and the amount shortened. We hypothesized that this was

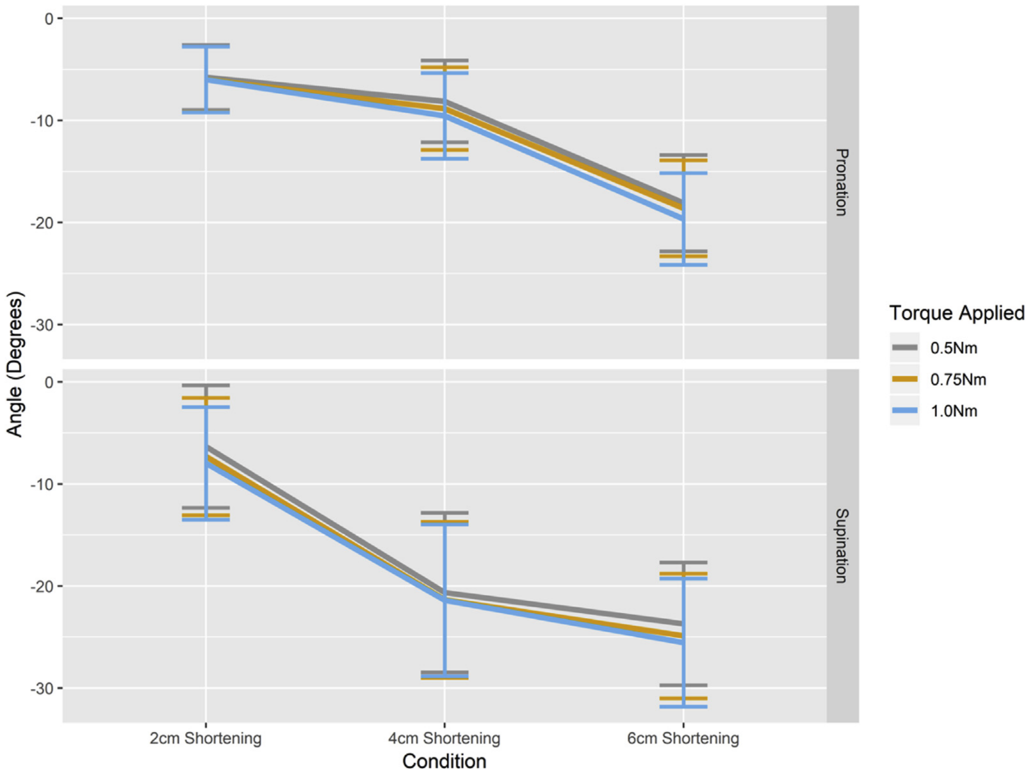

FIGURE 3: Changes in pronation (top) and supination (bottom) ranges of motion after shortening at different levels of loading.

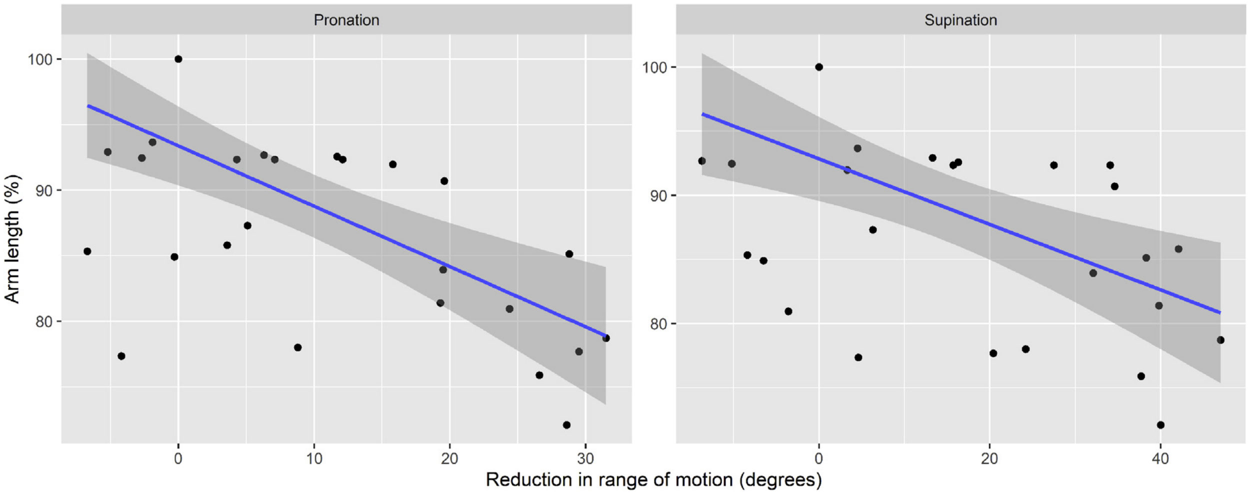

FIGURE 4: Changes in the range of motion against the percentage of the length of arms, including linear models.

related to the ability of our study design to control the amount of force exerted during the rotation. We found that supination decreased more between the 2-cm and 4-cm conditions, whereas pronation decreased more between the 4-cm and 6-cm conditions. This observation was consistent with the findings reported by Chauhan et al,[7] in which a patient with a comminuted both-bone fracture underwent 2 cm of shortening as a part of his initial procedure. The patient showed a decrease in supination to 45° as compared with 90° in the contralateral forearm. However, the patient's pronation only decreased to 80° as compared with 90° on the contralateral side.

We found that maintaining an anatomical relationship between the radius and ulna became substantially more difficult between the 2–4-cm and 4–6-cm osteotomy conditions; however, this method of fixation simulates the challenges faced by surgeons

TABLE 2. Changes in the Radial Bow and Radioulnar Gap Between Shortening Conditions

Condition	Anatomical Variables, Estimated Change (*P* Value, 95% CI) Radial Bow (mm)	Radioulnar Gap (mm)	Radial Bow Location (%)
Intact versus 2 cm	−4.8 (<.001, [−6.6 to −2.9])*	−5.3 (.001, [−9.0 to −1.6])*	−1.7 (.8, [−6.5 to 3.1])
Intact versus 4 cm	−6.0 (<.001, [−7.8 to −4.1])*	−4.5 (<.001, [−9.6 to −2.3])*	−7.5 (<.001 [−12.2 to −2.7])*
Intact versus 6 cm	−8.3 (<.001, [−10.1 to −6.4])*	−6.4 (<.001, [−11.9 to −4.5])*	−9.0 (<.001 [−13.8 to −4.2])*
2 cm versus 4 cm	−1.2 (.35, [−3.0 to 0.7])	1.1 (.97, [−4.3 to 3.0])	−5.7 (.011, [−10.5 to −0.9])*
2 cm versus 6 cm	−3.5 (.001, [−5.3 to −1.7])*	−0.8 (.18, [−6.6 to 0.78])	−7.3 (<.001, [−12.1 to −2.5])*
4 cm versus 6 cm	−2.3 (.006, [−4.1 to −0.5])*	−1.9 (.41, [−5.9 to 1.5])	−1.5 (.845, [−6.3 to 3.3])

*Statistically significant changes ($P < .05$).

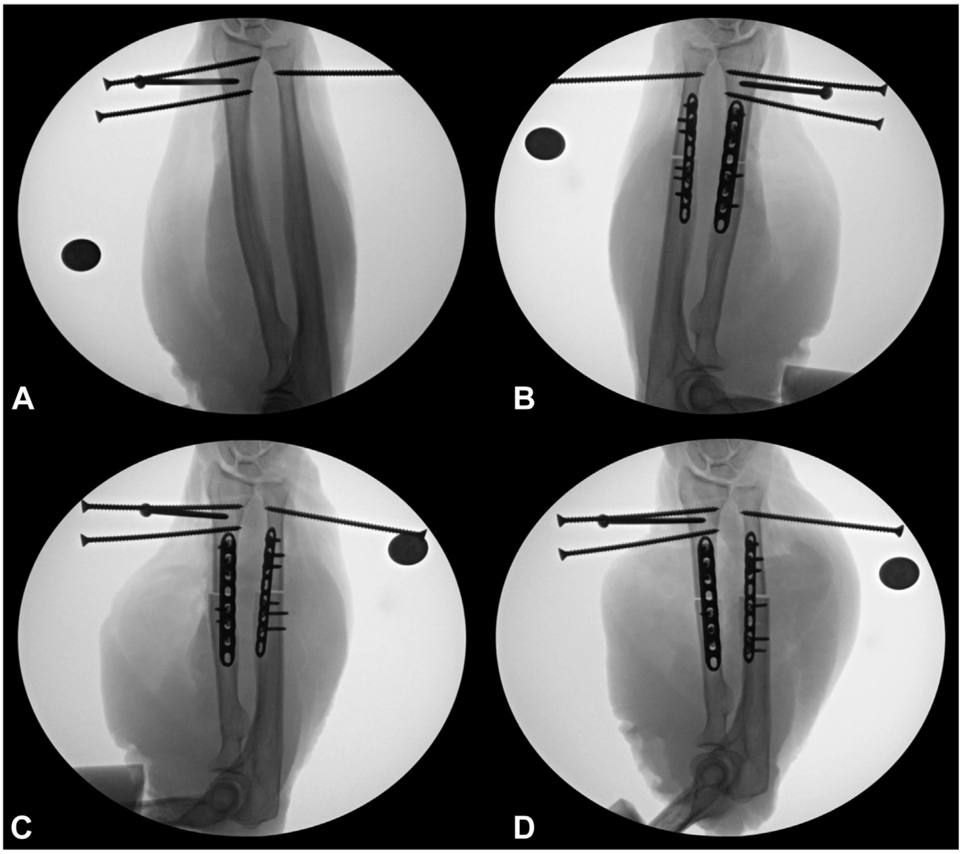

FIGURE 5: Radiographic images of key anatomic measurements for 1 specimen. **A** 0-cm condition. **B** 2-cm condition. **C** 4-cm condition. **D** 6-cm condition.

performing replantations at the forearm level. As the size of the bone resection increased, the gentle curve of the radius on its volar surface became nonanatomic, which affected the maximum radial bow and location of the radial bow. One interesting finding was an increase in the radioulnar gap between the 2-cm and 4-cm osteotomy conditions. We believe that this finding is related to the nonanatomical reductions following forearm shortening.

The results of this study offer insights into the results expected after forearm-level replantations, severely comminuted both-bone forearm fractures, infected nonunions of the forearm, and hand transplantations. To our knowledge, no large, follow-up studies related to forearm shortening have reported any effects on supination or pronation.[1,3,18]

The limitations of our study include its inability to model soft-tissue scarring that occurs following hand replantations. Although we maintained all the soft tissue of the elbow, forearm, and hand, we recognize that our results should be considered the best possible results that may be expected following one of these procedures. No reports on replantation cases have specifically discussed the soft-tissue envelope, creating a limitation related to supination/pronation; however, regarding both-bone fractures with a malunion, it has been discussed that repairs should be performed prior to 1 year to limit soft-tissue contracture.[19]

An additional limitation of our study is its applicability only to replantations of the middle third of the forearm. This region was selected because of its clinical relevance and to avoid injury to the distal oblique bundle of the interosseous membrane, which has been postulated to cause distal radioulnar joint instability.[20] Our study cannot be extrapolated to the proximal or distal thirds of the forearm. Prior cadaveric studies have shown that shortening osteotomies in different zones of the forearm may affect forearm motion to different degrees.[10]

Another limitation of our study involves its standardized 2-, 4-, and 6-cm shortenings despite nonstandardized cadaver forearm lengths. However, we feel that our results serve as a guide to the potential effects of shortening rather than dictate that a forearm should be shortened a specific amount. Patient counseling should address the topic of balancing the effects of forearm shortening with the ability to undergo a tension-free repair. Our last noted limitation includes challenges associated with fixation and performing reductions for larger bone resections, both of which reflect the challenges faced in clinical practice. The volar surface of the radius was used for plating, which is commonly employed in current practice.

We showed that forearm pronation is limited even by the smallest shortening increment studied (2 cm) within the mid-radius. Supination begins to be limited at 4 cm of shortening of the mid-radius. The forearm range of motion decreases as osseous shortening progresses from 2−6 cm. These findings may help patients and providers discuss the expected effect that forearm shortening may have on forearm range of motion.

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