Mechanical Evaluation of Four Internal Fixation Constructs for Scaphoid Fractures

HAND
2016, Vol. 11(1) 72–77
© American Association for
Hand Surgery 2016
DOI: 10.1177/1558944715614889
hand.sagepub.com

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Abstract

Background: The objective of this study was to compare the mechanical performance of 4 different constructs for fixation of oblique scaphoid fractures. **Methods:** Twenty-eight synthetic scaphoids underwent an oblique osteotomy along the dorsal sulcus. Each was randomly assigned to fixation by 1 of 4 methods: two 1.5-mm headless compression screws, one 2.2-mm screw, one 3-mm screw, or a 1.5-mm volar variable-angle plate. After fixation, scaphoids were potted at a 45° angle and loaded at the distal pole by a hydraulically driven mechanical testing system plunger until the fixation failed. Excursion and load were measured with a differential transformer and load cell, respectively. From these data, the stiffness, load-to-failure, and maximum displacement of each construct were calculated. **Results:** The 2.2-mm screw demonstrated the highest stiffness and the two 1.5-mm screws had the lowest. However, there were no significant differences among the fixation methods in terms of stiffness. Both 2.2- and 3-mm screw constructs had significantly higher loads-to-failure than two 1.5-mm screws. The maximum load for the plate approached, but did not achieve, statistical significance compared with the 1.5-mm screws. There was no significant difference among constructs in displacement. **Conclusions:** All constructs demonstrated similar mechanical properties that may provide sufficient stability for effective clinical use. Given their significantly higher loads-to-failure, a 2.2- or 3-mm screw may be superior to two 1.5-mm screws for fixation of unstable scaphoid fractures. The volar plate did not have superior mechanical characteristics to the compression screws.

Keywords: mechanics, fracture, internal fixation, scaphoid

Introduction

Scaphoid fractures are common injuries of the hand, accounting for approximately 60% of carpal fractures.¹⁵ Indications for operative fixation of scaphoid fractures (whether through percutaneous or open approaches) include, but are not limited to, fracture displacement, proximal pole fractures, unstable fractures, loss of carpal alignment, or delayed union secondary to a delay in diagnosis.^{13,23} Some reports have also advocated for osteosynthesis of nondisplaced scaphoid fractures in young, active patients to accelerate healing, permit early wrist motion, and avoid the potential complications of prolonged casting.²² Nonetheless, operative fixation of scaphoid fractures remains a challenging procedure, despite the various fixation constructs currently available.

The operative fixation of scaphoid fractures is typically performed with a single compression screw. However, if the wrist is repetitively mobilized on the operating table following fracture stabilization, there is the potential for loss of primary stability due to suboptimal rotational stability offered by a single screw. Consequently, this has led to the development of alternative methods of scaphoid fracture

fixation. Several studies have shown the importance of screw length and the central placement of screws for osteosynthesis of these fractures.^{6,21} However, no consensus exists regarding the optimal screw thread diameter.^{2,24} In addition, dual-screw fixation has been proposed as an alternative to single-screw constructs for nonunions and may demonstrate increased stability, which could also apply to acute fixation.¹⁰ Recently, successful volar plating of scaphoid nonunions suggests clinical potential for the fixation of acute scaphoid fractures.⁷ To our knowledge, however, no prior studies have compared the mechanical performances of single-screw constructs of varying screw thread diameters, dual-screw constructs, and volar plate constructs for the fixation of scaphoid fractures.

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The purpose of the present study was to assess the mechanical performance of 4 different constructs for fixation of oblique scaphoid fractures. An understanding of these mechanical characteristics can guide the orthopedic surgeon's implant selection to maximize fixation stability for effective clinical use. To accomplish this, we sought to assess, compare, and answer the following: What is the stiffness of each construct? What is the load-to-failure of each fixation method? And, what is the maximum displacement of each implant? These questions were tested in an axial loading model utilizing synthetic scaphoid bones.

Materials and Methods

Twenty-eight corticocancellous (soft type) synthetic scaphoids (SYNBONE, Malans, Switzerland) were utilized in this study. The overall experimental model was similar to that implemented in previous biomechanical studies.²¹ Each scaphoid underwent an oblique osteotomy along the dorsal sulcus with the aid of a precision thin-blade saw to simulate an unstable oblique fracture (Herbert type B1 with a dorsal sulcus pattern).¹⁴ This plane of osteotomy was chosen based on prior work that found that most scaphoid waist fractures are horizontal oblique, and not transverse as previously thought.²⁰ Furthermore, the dorsal sulcus pattern appears to be the most common subtype of oblique fractures.⁴ A smooth, rather than interdigitating (where the fractured sites have corresponding sections that "key in"), osteotomy cut was performed due to the challenges of replicating the same interdigitation pattern in several different osteotomies. Each scaphoid was then randomly assigned to undergo fixation by 1 of 4 different constructs ($n = 7$ per construct): two 1.5-mm headless compression screws (Synthes, Monument, Colorado), one 2.2-mm screw (Medartis SpeedTip CCS 2.2 cannulated compression screw, Exton, Pennsylvania), one 3-mm screw (Medartis SpeedTip CCS 3.0 cannulated compression screw, Exton, Pennsylvania), or a 1.5 mm volar variable-angle plate (Medartis TriLock 1.5 scaphoid plate, Exton, Pennsylvania). The single-screw constructs (2.2 and 3 mm) were inserted in the central position, whereas the dual compression screw fixations (two 1.5-mm screws) were implanted in equal distances from the central axis of the scaphoid in the eccentric peripheral thirds of the bone. Moreover, the volar scaphoid plate was applied to the scaphoid in the buttress mode with six 1.5-mm non-locking screws, 3 in each fragment (Figure 1). All screws were implanted by the same single investigator to 2-finger tightness to better simulate actual clinical practice.²⁵

After fixation, a Kirschner wire was introduced through the proximal pole of each scaphoid to further stabilize the specimen.²¹ This wire remained only within the proximal fragment and did not cross the fracture site. The scaphoids were then oriented at a 45° angle to the horizontal plane with the aid of another Kirschner wire (removed prior to testing)

Figure 1. Volar variable-angle plate fixation construct. (A) Radioscaphoid articulation view and (B) volar view.

Figure 2. Custom jig with potted scaphoid oriented at 45° to simulate a physiologic dorsal-to-volar cantilever load.

Note. The Kirschner wire was inserted to assist with obtaining the appropriate angle, and it was removed prior to mechanical testing.

in order to simulate a physiologic dorsal-to-volar cantilever load and were subsequently potted in this position in a custom jig with a filler resin (Bondo, 3M, Saint Paul, Minnesota; Figure 2). Each specimen was then loaded at the distal pole itself by a hydraulically driven plunger from a mechanical testing system (MTS) machine (Instron 2000, Eden Prairie, Minnesota). The load was increased until the fixation failed by bone fracture, implant deformity, or loss of reduction. The excursion and load were measured with a differential transformer and load cell, respectively. From these data, the stiffness, load-to-failure, and maximum displacement (displacement at failure) of each construct were calculated.

Failure was defined as a distinct change in the load-displacement curve. Stiffness was determined from the slope of the linear portion of the load-displacement curve. A sample size of 7 for each construct was selected as several prior scaphoid biomechanics studies have demonstrated that adequate power for statistical analysis (80% power with 95% confidence) can be achieved with sample sizes in this range.^{5,8,19} One-way analysis of variance tests were

Figure 3. Stiffness data for each fixation construct.
Note. Mean values and standard deviation bars are provided.

Figure 4. Load-to-failure data for each fixation construct.
Note. Mean values and standard deviation bars are provided.

performed to evaluate differences in stiffness, load-to-failure, and maximum displacement among the 4 fixation groups. Pairwise comparisons between groups were performed with Wilcoxon/Mann-Whitney *U* tests when applicable. The level of significance for all tests was $P < .05$.

Results

Of the fixation constructs, the 2.2-mm screw demonstrated the greatest stiffness (100.7 ± 33.1 N/mm, 95% confidence interval [CI], 66.0-135.5 N/mm) while the dual 1.5-mm screws had the lowest stiffness (74.9 ± 54.7 N/mm, 95% CI, 29.1-120.6 N/mm; Figure 3). There were no significant differences, however, among the fixation constructs with regard to stiffness ($P = 0.211$).

Statistical analysis revealed a significant difference in load-to-failure between groups ($P = .027$). Pairwise comparisons showed that both the 2.2-mm (492.8 ± 148.1 N, 95% CI, 337.4-648.2 N) and 3-mm (478.1 ± 96.7 N, 95% CI, 388.7-567.6 N) screw constructs had significantly higher loads-to-failure than the two 1.5-mm screws (302.4

± 89.2 N, 95% CI, 227.8-377 N; $P = .017$ and $.013$, respectively; Figure 4). Furthermore, volar plate fixation also demonstrated greater load-to-failure than dual 1.5-mm screw fixation (458.8 ± 166.9 N, 95% CI, 283.7-634 N), although this finding only trended toward, but did not achieve, statistical significance ($P = .061$). No other significant differences in load-to-failure were noted. All screw fixation constructs failed via screw migration. Volar plate constructs were irreversibly deformed (bent into more flexion) at the midpoint in all specimens.

As demonstrated in Figure 5, maximum displacement was lowest in the 2.2-mm screw group (8.6 ± 1.3 mm, 95% CI, 7.3-9.9 mm) and greatest in the volar plate group (11.9 ± 3.1 mm, 95% CI, 8.6-15.2 mm). However, no significant differences in maximum displacement were found between any fixation constructs ($P = .196$).

Discussion

The scaphoid bridges the proximal and distal carpal rows, thereby subjecting it to relatively constant bending/shearing

Figure 5. Maximum displacement data for each fixation construct. Note. Mean values and standard deviation bars are provided.

loads.¹¹ This, coupled with its tenuous vascular supply, the geometry of its fracture patterns, and its intra-articular nature, makes scaphoid fixation challenging.¹⁷ Advancements in operative management, including various screw and plate constructs, have helped to stimulate a movement toward early fixation of many scaphoid fractures.^{11,22} Despite the diversity of surgical implants, to the authors' knowledge, no previous investigations have evaluated the biomechanical performance of different single-screw, dual-screw, and volar plate constructs for scaphoid fracture fixation. The present study compared the mechanical stability of 4 different fixation constructs in an oblique scaphoid fracture model. This was accomplished by determining the stiffness, load-to-failure, and maximum displacement of each construct. Of note, our study may be the first to assess the biomechanics of volar plating in the context of scaphoid fracture fixation.

There are, however, limitations to this study. The linear osteotomy utilized in this study may not reflect the interdigitation or comminution often present at the fracture site that can lead to instability. In addition, the investigation was performed using an *in vitro* model with synthetic scaphoid bones, which does not account for the stabilizing effects conferred by surrounding ligamentous attachments. Consequently, the model may only serve as an approximation of *in vivo* mechanical stability. Nonetheless, prior studies have utilized synthetic bones in their investigations where about 50% of the scaphoid is potted in resin, as in the current study.^{5,12} Moreover, the current study used a relatively small sample size. However, the sample size is consistent with those utilized in numerous other scaphoid fracture studies.^{5,8,19} Also, no grafting techniques were utilized in the study; consequently, it is unclear if the results can be applied to a clinical nonunion where tricortical grafting may be used.

Stiffness is a commonly reported characteristic in orthopedic biomechanical studies, described as the resistance a

structure has to deformation.^{1,18,19} The adequate amount of stiffness for scaphoid fracture fixation in clinical practice, however, has not been clearly defined. The present study found no significant differences between fixation constructs with regard to overall stiffness. Nonetheless, the 2.2-mm screw had the highest mean stiffness, followed by the 3-mm screw and volar plate, with the two 1.5-mm screws demonstrating the lowest stiffness. Although the 3-mm screw's larger diameter would theoretically yield the stiffest construct, this was not observed in the present study possibly due to small fracturing around the 3-mm screw as it is a large implant relative to the size of the scaphoid. This is consistent with the current trend of using smaller diameter screws for scaphoid fixation. Interestingly, despite prior studies that have shown plate constructs to have higher stiffness than screws alone for upper extremity fractures, the volar plate had a comparatively lower stiffness (80.5 N/mm)³ relative to the various screw constructs (74.9-100.7 N/mm).³ Although six 1.5-mm screws are utilized to secure the plate, it is possible that the 0.8-mm low-profile thickness of the plate bridging the simulated fracture site was too low to resist higher loads. This is further supported by the observation that the plate failed by bending at its midpoint, where the osteotomy was placed. In a recent biomechanical investigation evaluating interpositional bone graft fixation for scaphoid nonunions, Koh et al noted that various single-screw constructs exhibited statistically similar stiffness values, ranging from 64.09 to 84.41 N/mm.¹⁸ In addition, Luria et al demonstrated identical stiffness values for 2.4-mm screws placed either perpendicular to an oblique scaphoid fracture line or in the center of the proximal fragment (131 N/mm).¹⁹ These quantitative and qualitative results are similar to those found in the present study, further validating our results. Any relatively slight differences in stiffness values could be attributable to the use of a cadaver model (used by Koh and Luria) as opposed to the synthetic bone utilized in the current study. Overall, the results of the present study,

as well as those of the aforementioned investigations, suggest that screw (and plate) selection does not significantly affect the overall stiffness of the fixation construct in scaphoid fracture models.

In addition to stiffness, load-to-failure is often cited as a measure of biomechanical stability. The term refers to the maximum force a structure can resist before it irreversibly fails. Similar to stiffness, load-to-failure values followed the same trend, with the 2.2-mm screw and two 1.5-mm screw constructs having the highest and lowest values, respectively. However, unlike stiffness, significant differences were noted in the load-to-failure of several constructs. Particularly, the 2.2- and 3-mm single-screw constructs had significantly higher loads-to-failure than the dual 1.5-mm screw method. This is likely secondary to their larger core diameter, as larger diameter screws better approximate the bending strength of the scaphoid.^{16,18} In addition, the two 1.5-mm screw constructs likely begin to fail as the first of the 2 screws fails, thereby failing at a single 1.5-mm screw failure point (regardless of the number of screws). Nonetheless, these results contrast with those of Koh et al, who found no significant differences in loads-to-failure among various screw constructs.¹⁸ The present study's values (302.4–492.8 N) were higher than those found in the aforementioned investigations by Koh et al (123.95–170.62 N) and Luria et al (137–148 N).^{18,19} However, loads-to-failure for screws of greater than 500 N have been reported in the scaphoid literature.²¹ The notably higher loads-to-failure in the present study may be due to the use of different screw implants and possible differences in the type of osteotomy introduced in other scaphoid models. Furthermore, although not statistically significant ($P = .061$), the volar plate demonstrated a higher load-to-failure than the two 1.5-mm screw fixation as well. The grid-like structure of the plate may distribute the applied force over a greater area, thereby enabling the construct to endure higher loads before failing.

Compared with stiffness and load-to-failure, displacement is less reported in the literature. Although larger diameter screws better resist lateral displacement, no significant differences in maximum displacement were found between any fixation constructs.⁹ Considering that there were no significant differences in maximum displacement or stiffness among the constructs, the significantly higher loads-to-failure seen with the 2.2- and 3-mm screws may indicate that they are superior to two 1.5-mm screws for fixation of unstable scaphoid fractures. In addition, although all constructs demonstrated properties that may provide sufficient stability for clinical use, the volar plate does not appear to have superior mechanical characteristics to compression screws. As the mechanical properties of the volar plate have yet to be enumerated in the literature, further research is needed to confirm this.

Ethical Approval

This study was exempt from review 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

No informed consent was obtained due to the anonymous nature of the report, with no identifying data utilized.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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