Biomechanical Strength of Scaphoid Partial Unions

Adam C. Brekke, MD¹ Mark C. Snoddy, MD¹ Donald H. Lee, MD¹ Marc J. Richard, MD²
Mihir J. Desai, MD¹

¹ Department of Orthopaedics and Rehabilitation, Vanderbilt University Medical Center, Nashville, Tennessee

² Department of Orthopaedic Surgery, Duke University, Durham, North Carolina

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Address for correspondence Adam C. Brekke, MD, Department of Orthopaedics and Rehabilitation, Vanderbilt University Medical Center, 1215 21st Avenue South, Medical Center East, South Tower Suite 3200, Nashville, TN 37232 (e-mail: adam.c.brekke@vanderbilt.edu).

Abstract

Background It remains unknown how much force a partially united scaphoid can sustain without refracturing. This is critical in determining when to discontinue immobilization in active individuals.

Purpose The purpose of this study was to test the biomechanical strength of simulated partially united scaphoids. We hypothesized that no difference would exist in load-to-failure or failure mechanism in scaphoids with 50% or more bone at the waist versus intact scaphoids.

Materials and Methods Forty-one cadaver scaphoids were divided into four groups, three experimental osteotomy groups (25, 50, and 75% of the scaphoid waist) and one control group. Each was subjected to a physiologic cantilever force of 80 to 120 N for 4,000 cycles, followed by load to failure. Permanent deformation during physiologic testing and stiffness, max force, work-to-failure, and failure mechanism during load to failure were recorded.

Results All scaphoids survived subfailure conditioning with no significant difference in permanent deformation. Intact scaphoids endured an average maximum load to failure of 334 versus 321, 297, and 342 N for 25, 50, and 75% groups, respectively, with no significant variance. There were no significant differences in stiffness or work to failure between intact, 25, 50, and 75% groups. One specimen from each osteotomy group failed by fracturing through the osteotomy; all others failed near the distal pole loading site.

Conclusion All groups behaved similarly under physiologic and load-to-failure testing, suggesting that inherent stability is maintained with at least 25% of the scaphoid waist intact.

Clinical Relevance The data provide valuable information regarding partial scaphoid union and supports mobilization once 25% union is achieved.

Keywords

- ▶ scaphoid fracture
- ▶ scaphoid union
- ▶ biomechanical strength

After adequate conservative or operative management, union is achieved in 90 to 98% of nondisplaced scaphoid waist fractures.^{1–4} Prolonged time to union as well as a higher nonunion rate has been demonstrated for displaced scaphoid fractures.^{5,6} Regardless of displacement, the serious consequences of nonunion, such as progressive degenerative changes and carpal collapse, have resulted in a restrictive treatment regimen with immobilization reaching 8 to 12 weeks.^{7–10}

Shortening the length of immobilization after scaphoid fractures, regardless of treatment, has been an area of keen interest.^{8,11–13} Computed tomography (CT) has been used to document, predict, and estimate the time to union.¹⁴ Previous studies have defined “union” as at least 50% bridging trabeculae, which can occur as early as 4 weeks.^{11,14,15} While partial or incomplete scaphoid unions have been shown to go onto uneventful union at final follow-up,¹⁵ it is not yet

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known how much force a partially united scaphoid can sustain without refracturing. This is particularly important in determining when to discontinue immobilization or allow return to activity in these individuals, especially laborers, athletes, or military personnel.

The purpose of this study was to test the biomechanical strength of simulated partially united scaphoids using validated testing models for scaphoid fractures.^{16–19} Partial unions of 25, 50, and 75% at the scaphoid waist were simulated and compared with intact scaphoids. We hypothesized that there would be no difference in the biomechanical load-to-failure or failure mechanism of scaphoids with 50% or more bone at the waist compared with intact scaphoids.^{11,15}

Materials and Methods

Cadaveric Specimens

Forty-one scaphoids were harvested from lightly embalmed cadaver specimens. The sample size was calculated based on load-to-failure means in Faucher et al, with $\alpha = 0.05$, $\beta = 0.20$ (for 80% power with 95% confidence), and $\sigma D = 40$, which resulted in eight scaphoids per group and is consistent with other biomechanical studies.^{16,19,20} We chose additional scaphoids to provide additional margin for safety. All soft tissue attachments were dissected from the scaphoids. None of the scaphoids showed any evidence of pathology. Scaphoids were randomly assigned to one of four groups—an intact scaphoid control group and three experimental groups consisting of oblique dorsoradial osteotomies in scaphoids involving 25, 50, and 75% of the width of the scaphoid waist. This randomization resulted in 10 scaphoids in each group, except in the 25% osteotomy group which had 11. The percentages and osteotomy location are based on CT studies of partial scaphoid unions.¹⁵

Partial Union Model

Osteotomies were created in each of the experimental group scaphoids using a technique adapted from previously published studies.^{19,21} To create a reproducible cut, the long axis of the scaphoid was identified and marked. A protractor was then used to indicate a line 45 degrees to the long axis and roughly in line with the dorsal sulcus. A caliper was used to measure the transverse depth of the narrowest portion of the scaphoid waist, and a line for the osteotomy was drawn out along the dorsal sulcus to simulate an oblique fracture pattern. To simulate different degrees of partial union, a thin-blade sagittal saw was used to create osteotomies, starting on the dorsoradial surface and carried to 25, 50, or 75% of the depth depending on the experiment group assigned. The 25% osteotomy group corresponds to 75% fracture union, and the 75% osteotomy represents only 25% bony union. Each specimen was potted in dental stone mix (US Gypsum, Chicago, IL) in 3.5" polyvinylchloride pipe using a tripod of Kirschner wires placed in the proximal pole to aid in anchoring the specimen within the cement. The specimens were positioned such that the waist and osteotomy were fully exposed and oriented with the marking on the long axis at 45 degrees to the horizontal. This simulates the anatomical position of the scaphoid during

normal physiologic loads and is the method adopted by prior models.^{16,17,19,21}

Mechanical Testing

Each specimen was loaded from the dorsal to volar direction with a compressive cantilever force, which has been shown to be the primary physiologic load encountered by the scaphoid.^{16,18} A materials testing machine (MTS Bionix, Eden Prairie, MN) with a servohydraulic linear variable displacement transducer fitted with a ± 14.5 kN biaxial load cell (Tovey Engineering, Phoenix, AZ) was used to perform the load testing (►Fig. 1). The specimens were first subjected to a cyclic loading phase from 80 to 120 N at 1 Hz sinusoidal waveform, which is the subload to failure physiologic load protocol based on prior studies and pilot testing.^{16,19,20} The cyclic physiologic testing was performed until either a 2-mm displacement occurred (measured as the relative change in the linear variable displacement transducer) or all 4,000 load cycles were reached. This testing protocol and the 2-mm displacement threshold are based on previous study designs.^{16,19,20} After cyclic physiologic testing was complete, each specimen that withstood the physiologic testing without failure was subjected to load-to-failure testing while in the same position. Load was increased at 3 N/s until failure, which was defined as displacement of 2 mm, indicating fracture through the osteotomy or elsewhere in the distal scaphoid. Mechanism of failure for each specimen was recorded.

Fig. 1 Example of potted cadaveric specimen mounted in MTS testing machine with the servohydraulic transducer contacting the distal pole. Dotted black line on dorsal sulcus oriented 45 degrees to the long axis. Dotted red line represents orientation of osteotomies 25, 50, or 75% of the width of the scaphoid (from right to left in this image).

Table 1 Average values during cyclic physiologic subfailure conditioning

	N	Creep (mm)			Permanent deformation (mm)		
		Average	Standard deviation	p-Value	Average	Standard deviation	p-Value
Intact	10	0.20	0.12	0.65	1.42	1.57	0.34
25%	11	0.64	1.01		2.13	1.26	
50%	10	0.25	0.12		2.42	1.13	
75%	10	0.19	0.12		1.82	1.32	

Data Analysis

We compared the number of cycles survived, force (N), creep (mm), and permanent deformation (mm) during the cyclic physiologic testing and stiffness, maximum force to failure (N), work to failure (N·mm), and mechanism of failure during load-to-failure testing. Analysis of variance between groups was determined using the Kruskal–Wallis' nonparametric test. Modes of failure were compared using the Fisher's exact test. Statistical significance was established at $p \leq 0.05$.

Results

The specimen preparation, partial union model, and testing methods adequately replicated the previously published models. Biomechanical testing revealed that all scaphoids survived the 4,000 cycles of physiologic testing. All scaphoids were subjected consistently to the intended target forces of 80 to 120 N. All scaphoids survived the cyclic physiologic load testing and as such, no scaphoids experienced displacement of 2 mm when cycling from 80 to 120 N. The total creep, the difference of the displacement at 80 N from the first cycle to the last, was 0.20 mm for intact scaphoids and 0.64 mm for 25%, 0.25 mm for 50%, and 0.19 mm for 75% ($p = 0.65$) osteotomy groups. There was no significant difference across the four groups in permanent deformation ($p = 0.34$) defined as the difference of the displacement at 120 N from the first cycle to the last cycle (►Table 1).

Intact scaphoids endured an average maximum load of 334 N prior to failure, compared with 321 N for the 25% group, 297 N for the 50% group, and 343 N for the 75% group, with no statistically significant variance ($p = 0.86$) (►Fig. 2).

Fig. 2 Load-to-failure testing results for the intact versus each osteotomized group. Median values (solid line), first and third quartiles (upper and lower limits of box), and standard deviation (error bars) are represented.

There were no statistically significant differences in stiffness ($p = 0.15$) or work to failure ($p = 0.93$) between the intact, 25, 50, and 75% groups (►Table 2).

The most common mode of failure for all groups was a distal pole fracture distant to the osteotomy. The distal pole was the site at which the cantilever force was applied and fractured via a shearing mechanism. This occurred in 38 of the 41 scaphoids (►Fig. 3). One of the scaphoids from each experimental group failed via a fracture through the osteotomy site ($p = 0.99$) (►Fig. 4).

Discussion

The optimal duration of immobilization after scaphoid waist fracture remains unknown, partly due to the unproven strength of the partially united and still healing fracture. This study aimed to compare the biomechanical strength of simulated partial scaphoid unions. The three osteotomies, representing varying degrees of partial union, behaved similarly under cyclic physiologic testing, showing no statistical variation. As well, the three groups showed no significant variation during load-to-failure testing.

This study has several limitations. The biomechanical conditions in vivo are difficult to replicate using cadaver scaphoid specimens stripped of their soft tissue attachments. Specifically, our cyclic and load-to-failure testing consisted only of a cantilever bending force. Though this is a physiologic force, it does not fully account for the multidirectional forces the scaphoid endures in vivo. It is not known whether the biomechanical properties of the healing trabecular bone are identical to the remaining normal cortical bone of the osteotomized scaphoid in this model. Thus, there is a risk that these biomechanical results are overstated. We tested only a limited number of specimens; lightly embalmed cadaver specimens with scaphoids free of pathology are not a plentiful resource. However, 10 scaphoids in each group are slightly more than similar cadaveric studies with adequate power.^{16,19,20} We also did not standardize our model in regard to age or bone density. Finally, there is an increased trend to operative fixation of scaphoid fractures. Further investigation is required to understand the contribution of a compression screw to the biomechanics of partial union.

Maximum load to failure averaged 334 N for intact scaphoids and 321, 297, and 343 N for the 25, 50, and 75% groups, respectively. Our data are consistent with Meermans et al in a recent comparison of two fixation approaches in a scaphoid waist fracture model, which found the stronger

Table 2 Average values during load-to-failure testing

	N	Load to failure (N)			Stiffness (N/mm)			Work to failure (N·mm)		
		Average	Standard deviation	p-Value	Average	Standard deviation	p-Value	Average	Standard deviation	p-Value
Intact	10	334	119.81	0.86	263	148	0.15	781	446	0.93
25%	11	321	92.64		271	148		720	380	
50%	10	297	49.89		194	136		655	277	
75%	10	343	134.74		168	105		703	371	

transtrapezial fixation group displaced 2 mm at 324 N with a 386-N load to failure.²¹ Faucher et al created a dorsal sulcus oblique fracture model and found that screws placed perpendicular to the fracture line had an average of 258 N load to failure versus 294 N for screws placed in line with the central axis of the scaphoid.¹⁹

Fracture at the distal pole, near the cantilever loading site, was the mechanism of failure for 38 of 41 specimens, including all of the intact scaphoids and all but one of each of the experimental groups. This finding is also consistent

Fig. 3 Scaphoid specimen after load to failure resulted in fracture through distal pole, distant from osteotomy site.

with the common mechanism of failure seen by Faucher et al, with six of eight specimens fracturing at the distal pole in biomechanical testing.¹⁹ This suggests that the distal bone itself failed before the remaining scaphoid waist bone succumbed to the cantilever force which has been shown to replicate physiologic loading.^{16,17}

The lack of precipitous decline in biomechanical strength between osteotomy groups during either phase of testing suggests that inherent stability is not significantly killed as long as at least 25% of the scaphoid waist is intact. Therefore, during the fracture healing process, union and bridging trabeculae consisting of at least 25% of the scaphoid waist may be sufficient for the scaphoid to endure normal physiologic load.

This study shows that scaphoid partial union comprising at least 25% exhibits similar biomechanical strength to fully united scaphoid fractures and supports early return to motion and activity prior to full radiographic healing. We believe that this finding lends support to the trend to discontinue immobilization without exposing patients to undue risk of displacement or refracture. This conclusion is supported by Dunn et al, who recently described an early active motion rehabilitation protocol in a small series of consecutive, active duty military patients who experienced excellent functional outcomes and satisfaction at 1 year follow-up with evidence of healing on CT scan at 8 weeks and no complications.¹³ The potential benefits of earlier

Fig. 4 Scaphoid specimen after load to failure resulted in fracture through the 25% osteotomy.

mobilization for scaphoid fracture patients, who are often young laborers, include an earlier return to work, service or sport which reduces lost wages, lost productivity, and expenses related to disability.

Note

The work for this study was performed at the Vanderbilt University Medical Center.

Ethical Approval

This study is exempt from the internal review board because it is a biomechanical study using deidentified donated cadaver scaphoids.

Conflict of Interest

None.

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