EDITOR'S CHOICE

Scaphoid Healing Required for Unrestricted Activity: A Biomechanical Cadaver Model

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Purpose To determine if scaphoid fractures with bridging bone of 50% of their width treated with a centrally placed screw will restore biomechanical integrity equivalent to that of the intact scaphoid.

Methods Twenty-four fresh cadaver scaphoids were used. Six were left intact to serve as the control group. Six were osteotomized 50% of their width and made up the osteotomy without screw group. Six were included in the 50% osteotomy plus compression screw group. The remaining 6 were to be treated with an osteotomy of 25% or 75% with a screw, based upon the results of the 50% osteotomy with screw group. Biomechanical testing was performed using an Instron testing machine, with a load applied to the scaphoid's distal pole. Load to failure and stiffness were measured.

Results Intact scaphoids had an average load to failure of 610.0 N. The average load to failure of the 50% osteotomy group without a screw was 272.0 N and with a screw was 666.3 N. There was no significant difference in load to failure between the 50% osteotomy plus screw and the intact scaphoid. The 75% osteotomy plus screw was found to have a load to failure of 174.0 N, significantly lower than the intact scaphoid. The 50% osteotomy plus screw had a significantly higher stiffness than the intact scaphoid control.

Conclusions A 50% intact scaphoid with a centrally placed screw showed similar load to failure and significantly higher stiffness than the intact scaphoid when tested in cantilever bending.

Clinical relevance This study demonstrates that patients with scaphoid waist fractures who undergo surgery with a compression screw may be able to return to unrestricted activity with 50% partial healing. *(J Hand Surg Am. 2018;43(2):134−138. Copyright © 2018 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Scaphoid fracture, scaphoid nonunion, screw, partial.

THE SCAPHOID IS THE MOST COMMONLY FRACTURED carpal bone, yet treatment remains problematic.[1] The scaphoid heals more slowly than other bones owing to its limited blood supply and lack of periosteum. In the United States, it has been estimated that 345,000 scaphoid fractures occur annually and that, even with appropriate treatment, at least 5% fail to unite.[2−4] Complications of scaphoid fractures are frequent including delayed union, nonunion, arthritis, reduced wrist motion, and loss of strength.[4−6]

Surgery to address scaphoid fracture nonunion is not a guaranteed success. Surgical repair of a scaphoid nonunion has reported success rates ranging from 50% to 95%.[1,6−9] Successfully repaired scaphoid nonunions require, on average, an additional 6 months to heal.[1,6−9] Clinically, there is a subset of scaphoid fractures that heal with partial union. Serial computed tomography (CT) imaging

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Medartis (Basel, Switzerland) donated titanium headless compression screws. Medartis had no role in study planning, in the collection, analysis and interpretation of data, in writing the report, and in the decision to submit the article for publication.

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demonstrates partial union across the fracture site, and it is questionable whether these fractures will progress toward further union.[10,11]

The degree of partial healing sufficient to allow unrestricted use of the wrist remains unclear. To date, there have been no biomechanical or clinical studies defining how much bridging bone across a fracture site would be necessary to mimic the native, uninjured scaphoid. The use of headless compression screws adds to scaphoid stability and strength in the healing fracture.[12–15] We hypothesized that bridging bone of 50% of the scaphoid width with a centrally placed screw would restore scaphoid biomechanical integrity. Clinically, this would allow a treating physician to be confident that a partially united scaphoid fracture with a centrally placed headless compression screw is as strong as the uninjured bone, thus allowing patients to return to unrestricted activity without further treatment.

MATERIALS AND METHODS

Twenty-four fresh cadaver scaphoid specimens were obtained and cleaned of all soft tissue. The density of the scaphoids was calculated using Archimedes principle (mass/volume by displacement).[16] Six scaphoids were left intact to serve as the control group. The remaining scaphoids were osteotomized to varying degrees on the dorsal side of the anatomical waist, transverse to the longitudinal axis of the bone, to simulate a scaphoid waist fracture. The osteotomy was made with a scroll saw and measured with digital calipers. After osteotomy, there was a small dorsal gap of less than 2 mm, corresponding to the width of the saw blade, in the partial osteotomy specimens. Six scaphoids were osteotomized 50% of the scaphoid width to simulate a 50% healed scaphoid waist fracture. These made up the osteotomy without screw group. Six scaphoids were osteotomized 50% of the scaphoid waist and a titanium headless compression screw, with a modulus of elasticity similar to cortical bone, was placed down the central axis of the scaphoid according to the manufacturer's recommendations. These made up the 50% osteotomy plus compression screw group. The remaining 6 scaphoids were planned to be treated similarly with an osteotomy of 25% or 75% based upon the results of the 50% osteotomy group. If the 50% osteotomy with a scaphoid screw group had similar load to failure of the intact scaphoid group, a second round of testing with 25% of the scaphoid intact was to be performed. If the 50% osteotomy with a scaphoid screw group was not as mechanically sound as the intact scaphoid group, a second round of testing with 75% of the scaphoid intact was to be performed. Scaphoids were randomly assigned to the 4 study groups.

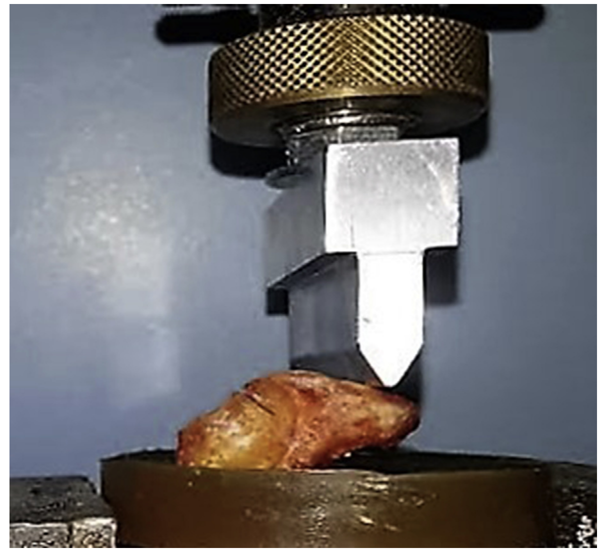

FIGURE 1: Photograph of experimental setup. This photograph demonstrates testing of a scaphoid with a 50% osteotomy without screw. The scaphoid was oriented at a 45° angle to the horizontal plane and the load was applied in a dorsal-to-volar orientation. The plunger loaded the scaphoid at a rate of 0.014 mm/s. The load was increased until catastrophic failure (fracture or loss of reduction) occurred.

The Medartis 3.0-mm headless compression screw was utilized (Medartis, Basel, Switzerland). The diameter was kept the same for all specimens. The length of the screw was determined by the length of the scaphoid, which was measured with digital calipers. Screws with a length 4 mm less than the scaphoid length were chosen to keep the screw subchondral.

The mechanical testing protocol has been validated by several studies.[12,15] For biomechanical testing, the scaphoids were potted in a holder with a polyurethane epoxy. A Kirschner wire was inserted in the proximal aspect of the scaphoid to provide additional anchoring stability. The scaphoid was oriented at a 45° angle to mimic the normal position of the scaphoid in the wrist. This enabled a dorsal to volar cantilever bending load, which represents the mode of failure of scaphoid nonunions with a screw in place. The scaphoid was then placed in an Instron testing machine where a pneumatically driven plunger applied the load to the distal pole at a rate of 0.014 mm/s until failure (Fig. 1). The load was increased for all specimens until the fixation failed by fracture or catastrophic loss of reduction. The load at failure was recorded and was determined at the first failure peak graphically, which corresponded to catastrophic loss of reduction or fracture of the bone. Stiffness was calculated from the slope of the force/displacement curve.

The number of scaphoids studied represented a sample of convenience and a power analysis was not performed. Statistical analysis was performed using analysis of variance to compare the mean values of the various groups regarding load to failure, stiffness, and densities. We then performed post hoc pairwise comparisons using Tukey-Kramer honest significant difference test.

RESULTS

Density was calculated using the Archimedes principle on all specimens. Scaphoid specimen densities averaged 1.22 g/cm^3 (SD ± 0.17 g/cm^3), similar to a prior report.[17] The average densities and ranges for each group were as follows—intact scaphoid: 1.25 g/cm^3 (range, 1.04−1.45 g/cm^3); 50% osteotomy: 1.12 g/cm^3 (range, 0.92−1.28 g/cm^3); 50% osteotomy with screw: 1.25 g/cm^3 (range, 1.02−1.42 g/cm^3); and 75% osteotomy with screw: 1.22 g/cm^3 (range, 0.81−1.45 g/cm^3). Load to failure was calculated for all specimens. The intact scaphoids had an average load to failure of 610.1 N (range, 554.8−674.2 N; SD ± 52.4). The 50% osteotomy group without a screw had an average load to failure of 272.1 N (range, 208.9−341.1 N; SD ± 54.4). When a headless compression screw was placed down the center of the scaphoid, the average load to failure was 666.3 N (range, 530.6−837.8 N; SD ± 121.5) (Fig. 2).

A greater load to failure was found for the intact scaphoid group than the 50% osteotomized scaphoid group ($P < .05$). When the intact scaphoid was compared with the 50% osteotomized scaphoid plus compression screw, a similar load to failure was found. Based upon this finding, the remaining 6 scaphoid specimens were osteotomized 75% of the width of the scaphoid waist, and a headless compression screw was placed as described previously. The 75% osteotomy plus screw group was found to have a load to failure of 174.0 N (range, 75.6−267.3 N; SD ± 77.9). This group was then compared with the intact scaphoid group. The 75% osteotomy group was found to have a lower load to failure ($P < .05$).

In addition, stiffness among the 4 groups of scaphoids were compared (Fig. 3). The 50% osteotomy plus screw group had the highest measured stiffness (263.4 N/m) and the 75% osteotomy plus screw group the lowest stiffness (34.3 N/m). The intact scaphoid was less stiff than the 50% osteotomy plus screw (158.6 N/m; $P < .05$), but was stiffer than the 50% osteotomy and 75% osteotomy plus screw groups ($P < .05$).

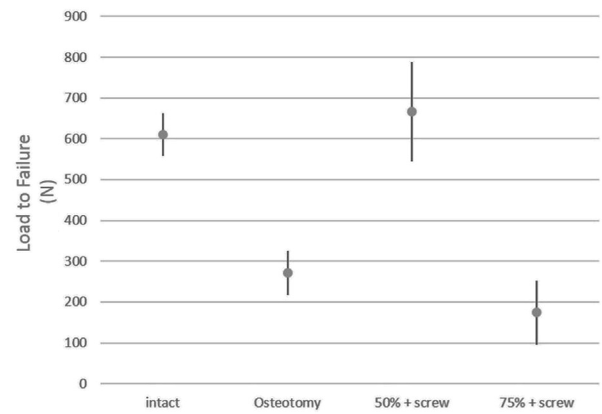

FIGURE 2: Load to failure of the various tested scaphoid study groups measured in N. Intact = intact scaphoid; Osteotomy = 50% osteotomized scaphoid without screw; 50% + screw = 50% osteotomized scaphoid with screw; 75% + screw = 75% osteotomized scaphoid with screw. The central point is the group mean and the vertical lines represent the SD of each group.

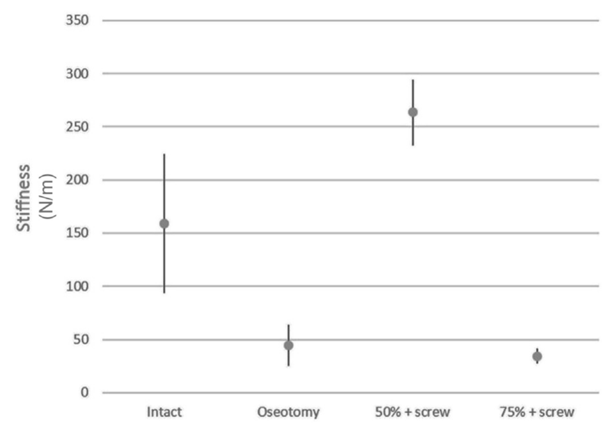

FIGURE 3: Stiffness of the various tested scaphoid study groups. Stiffness is measured in N/m. The central mark is the mean and the vertical lines represent the range. Intact = intact scaphoid; Osteotomy = 50% osteotomized scaphoid without screw; 50% + screw = 50% osteotomized scaphoid with screw; 75% + screw = 75% osteotomized scaphoid with screw. The central point is the group mean and the vertical lines represent the SD of each group.

DISCUSSION

The purpose of this study was to estimate the percentage of bridging bone necessary to provide a scaphoid fracture treated with a headless compression screw equivalent biomechanical stability to that of an intact scaphoid. Our hypothesis was that 50% bridging bone plus a headless compression screw would restore the scaphoid's native biomechanical integrity.

According to this study, a 50% intact scaphoid waist combined with a headless compression screw resulted in comparable biomechanical stability with that of an intact scaphoid. However, when the intact waist was reduced to 25% and combined with a screw, there was significantly decreased stability and the scaphoids failed at much lower loads. These results suggest that a scaphoid fracture treated with a headless compression screw and less than 50% bony healing on imaging are at higher risk for fracture fixation failure and should be kept protected with restricted activity, limited weight bearing and immobilization. In addition, scaphoid fractures that show healing of 50% or greater treated with a screw should be allowed unrestricted activity. Scaphoids with 50% of the waist intact without a screw in place showed significantly less stability than the intact scaphoid suggesting that patients being treated nonsurgically with only 50% bony healing should continue to be treated and protected.

Authors have anecdotally stated that return to unrestricted activity is predicated on 50% healing on CT scan; however, we are not aware of any studies confirming the accuracy of this value.[5,18] For this reason, we designed the current cadaver study. Dias[19] described the "clinical union," a state in which function can be resumed with "little risk of adversely influencing healing." Clinical union can be obtained faster with the use of an implant to share the transmission of load as seen in the scaphoid fracture with compression screw.[19] Based upon our results, it can be inferred that clinical union is obtained in scaphoid fractures treated with compression screws and 50% partial union.

There are limitations to this study. The fact that this is a biomechanical study using scaphoids with all soft tissue removed, calls into question the generalizability of these results to *in vivo* behavior of the scaphoid. In addition, our testing protocol simplified the forces mimicking physiological loads into a single vector, which may not accurately simulate the forces experienced by the scaphoid *in vivo*. We also did not perform cyclic loading, which may have led to weakening of the fixation over time. In addition, the densities of the specimens were measured using Archimedes principle. Density may have been better measured using CT scanning to provide a more accurate measurement of scaphoid density. Also, the 50% osteotomy group had a smaller density than the other 3 groups, and this may have influenced the decreased load to failure we found in this group. In addition, the linear osteotomy used to simulate a scaphoid waist fracture does not mimic the interdigitating and unique pattern of fracture healing of an *in vivo* scaphoid fracture. Finally, the fact that our study size was a sample of convenience, and not adequately powered, limits the validity of some of the statistical comparisons we made between groups, and a larger study with a proper power analysis should be performed in the future.

According to the results of this cadaver model, scaphoids that are 50% intact with a centrally placed screw show similar load to failure as an intact scaphoid when tested in cantilever bending. The results in this study provide the hand surgeon useful information regarding when to stop immobilization and when to allow a return to unrestricted activity in patients with scaphoid fractures with 50% bony healing treated with headless compression screws.

REFERENCES

1. Chang MA, Bishop AT, Moran SL, Shin AY. The outcomes and complications of 1,2-intercompartmental supraretinacular artery pedicled vascularized bone grafting of scaphoid nonunions. *J Hand Surg Am*. 2006;31(3):387−396.
2. Berger RA, Kauer JM, Landsmeer JM. Radioscapholunate ligament: a gross anatomic and histologic study of fetal and adult wrists. *J Hand Surg Am*. 1991;16(2):350−355.
3. Osterman AL, Mikulics M. Scaphoid nonunion. *Hand Clin*. 1988;4(3):437−455.
4. Schadel-Hopfner M, Marent-Huber M, Gazyakan E, Tanzer K, Werber KD, Siebert HR. Acute non-displaced fractures of the scaphoid: earlier return to activities after operative treatment. A controlled multicenter cohort study. *Arch Orthop Trauma Surg*. 2010;130(9):1117−1127.
5. Fowler JR, Hughes TB. Scaphoid fractures. *Clin Sports Med*. 2015;34(1):37−50.
6. McQueen MM, Gelbke MK, Wakefield A, Will EM, Gaebler C. Percutaneous screw fixation versus conservative treatment for fractures of the waist of the scaphoid: a prospective randomised study. *J Bone Joint Surg Br*. 2008;90(1):66−71.
7. Little CP, Burston BJ, Hopkinson-Woolley J, Burge P. Failure of surgery for scaphoid non-union is associated with smoking. *J Hand Surg Br*. 2006;31(3):252−255.
8. Kilic A, Sokucu S, Parmaksizoglu AS, Gul M, Kabukcuoglu YS. Comparative evaluation of radiographic and functional outcomes in the surgical treatment of scaphoid non-unions. *Acta Orthop Traumatol Turc*. 2011;45(6):399−405.
9. Mani KCK, Acharya P. Scaphoid nonunion: does open reduction, bone grafting and Herbert screw fixation justify the treatment? [published online ahead of print August 1, 2017]. *Int Orthop*. https://doi.org/10.1007/s00264-017-3590-3.
10. Amirfeyz R, Bebbington A, Downing ND, Oni JA, Davis TR. Displaced scaphoid waist fractures: the use of a week 4 CT scan to predict the likelihood of union with nonoperative treatment. *J Hand Surg Eur Vol*. 2011;36(6):498−502.

11. Singh HP, Forward D, Davis TR, Dawson JS, Oni JA, Downing ND. Partial union of acute scaphoid fractures. *J Hand Surg Br*. 2005;30(5):440−445.
12. Luria S, Lenart L, Lenart B, Peleg E, Kastelec M. Optimal fixation of oblique scaphoid fractures: a cadaver model. *J Hand Surg Am*. 2012;37(7):1400−1404.
13. Newport ML, Williams CD, Bradley WD. Mechanical strength of scaphoid fixation. *J Hand Surg Br*. 1996;21(1):99−102.
14. Toby EB, Butler TE, McCormack TJ, Jayaraman G. A comparison of fixation screws for the scaphoid during application of cyclical bending loads. *J Bone Joint Surg Am*. 1997;79(8): 1190−1197.
15. McCallister WV, Knight J, Kaliappan R, Trumble TE. Central placement of the screw in simulated fractures of the scaphoid waist: a biomechanical study. *J Bone Joint Surg Am*. 2003;85-A(1):72−77.
16. Heddle T. *Calculations in Fundamental Physics*. 1st ed. New York: Pergamon Press; 1971.
17. Madeley NJ, Stephen AB, Downing ND, Davis TR. Changes in scaphoid bone density after acute fracture. *J Hand Surg Br*. 2006;31(4):368−370.
18. Belsky MR, Leibman MI, Ruchelsman DE. Scaphoid fracture in the elite athlete. *Hand Clin*. 2012;28(3):269−278, vii.
19. Dias JJ. Definition of union after acute fracture and surgery for fracture nonunion of the scaphoid. *J Hand Surg Br*. 2001;26(4):321−325.