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Original Research

Effect of Bicortical Interfragmentary Screw Size on the Fixation of Metacarpal Shaft Fractures: A 3-Dimensional-Printed Biomechanical Study



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Purpose: Spiral metacarpal fractures fixed with 2 non-lagged, interfragmentary cortical screws were tested to failure. The effect of screw size (1.2 mm, 1.5 mm, 2.0 mm, and 2.3 mm) on construct strength was tested in 3-point bending.

Methods: Three-dimensional-printed metacarpal test models were reproduced from computed tomography scans to reduce the confounding variables of bone density and anatomy, often encountered when using cadavers.

Results: No significant difference was found between the screw sizes, and the peak failure force was similar. Drill bit fracture and deformation during the insertion of the smallest screw (1.2 mm) as well as model failure during the insertion of the largest screw (2.3 mm) were found in some cases.

Conclusions: Screws of 1.5 mm and 2.0 mm in diameter were of sufficient strength and did not have the issues encountered with smaller or larger screws. Concerns from previous authors regarding intra-operative fracture were consistent with the pre-testing failure of some 2.3-mm models.

Clinical Relevance: Screws of 1.5 mm or 2 mm appear adequate for the fixation of spiral fracture patterns in metacarpal shafts using bicortical non-lagged technique with a low risk of fixation complications.

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Metacarpal shaft fractures are common injuries and can be classified by pattern as transverse, short oblique, long oblique, spiral, comminuted, and those that are a part of larger traumatic injuries.^{1–3} These patterns denote stability and guide management options.^{3–5} Many of these fractures can be managed non-operatively using intrinsic-plus casting, buddy strapping, and thermoplastic splints, with good functional outcomes reported.^{1,2,6} However, indications to fix surgically include instability, irreducible fractures, clinical rotational deformity, intra-articular extension, open injuries, and those that are a part of multiple hand injuries and polytrauma.^{1,4–7} Long oblique fractures are defined by the

fracture length being at least twice the diameter of the diaphyseal bone through which they traverse. These, along with spiral fractures, are unstable because of loss of compression at the fracture interface, allowing intrinsic and extrinsic muscle forces to shorten, angulate, and cause axial deformity.^{4,5} This loss of bony integrity can lead to unacceptable healing patterns and subsequent functional losses.

There are many fixation options for these injuries, and much of the practice is dependent on surgeon preference and experience as opposed to evidence-based results.^{1,2,6,7} Methods may stand alone or in combination and include Kirschner wires (K-wires), interfragmentary screws, headless intermedullary screws, cerclage and tension band constructs, and plates. K-wires are extremely versatile, relatively inexpensive, and useful fixation devices but stability, migration, loosening, and pin track infection are concerns.⁶ Plates and screws provide greater stability but may lead to problems with prominence and adhesion development. There is a potential risk of periosteal devascularization as well as stress

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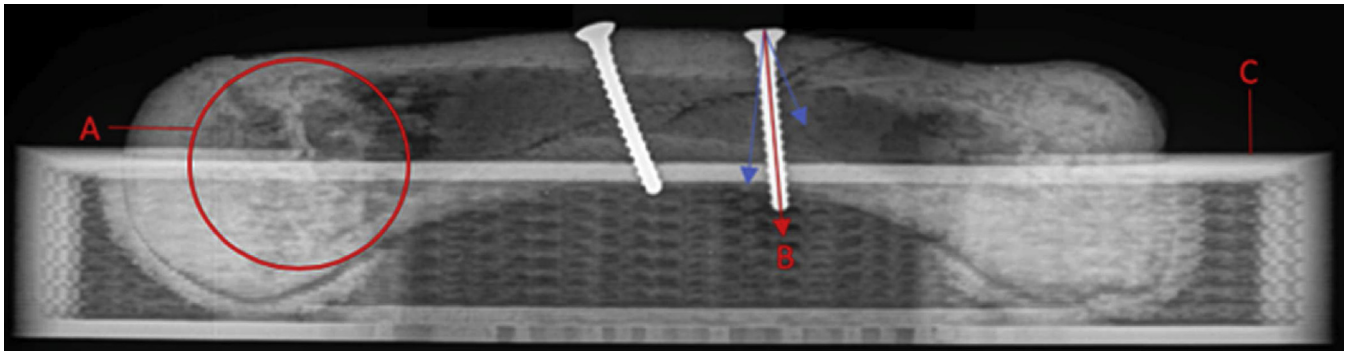


Figure 1. Fixed metacarpal fracture before stress testing. A Meta-diaphyseal trabecular pattern produced in acrylonitrile butadiene styrene printer. B “Perfect screw” vector between lines perpendicular to the shaft and fracture line. C Orthogonal 3-dimensional-printed jig.

shielding secondary to the rigidity they afford.^{4–6} As such, screws without plate fixation have gained popularity to bridge these compromises, and many authors suggest these as the method of choice in spiral and long oblique metacarpal fractures.^{8–10} Intraoperative image intensification has increased surgeon confidence in the accuracy of insertion and, therefore, the success of this fixation method.⁵ Screw fixation allows for early range-of-motion while minimizing the soft tissue trauma and subsequent tethering, particularly if used in a percutaneous manner.^{5,8,10} Uncertainties still exist as to the surgical technique that provides the most stable fixation. Some authors recommend the placement of at least 2 screws, 1 perpendicular to the fracture line to provide compression and the other perpendicular to the long axis of the shaft to resist shear.^{1,3,5,9} Others recommend 2 screws directed in a vector between the shaft axis and fracture line as an alternative as shown in Figure 1.⁹ Day³ suggests that the placement should be at least 2 screw diameters from the fracture line whereas Henry⁴ recommends spacing of at least a full screw head diameter.^{3,4} Using a lag technique for compression with cortical screws is standard practice in fracture fixation throughout the body, and the hand is no exception. However, Roth and Auerbach¹¹ reported this as an unnecessary step backed by their case series over an 8-year period and showed good results with bicortical non-lagged screws in metacarpal and phalangeal fractures. This is supported by biomechanical data and is currently our practice.¹²

The literature also lacks consistency regarding the most appropriate size of these interfragmentary screws. For metacarpal spiral fractures, Geissler⁹ recommends two 1.5-mm or 2-mm screws whereas Day³ recommends two 2.7-mm screws as a minimum in larger patients and three 2.0-mm or 2.4-mm screws in smaller patients. Henry⁴ suggests a 2.0-mm diameter is too large to be used as a lag screw in this setting and recommends 1.5 mm as an adequate size, lowering to 1.3 mm in proximal phalanges.

What is clear is a disparity in expert consensus as well as a wide range of results due to the use of cadaveric tissue. The aim of the current study was to use a novel method to create reproducible metacarpal models that replicate a clinical spiral fracture and use these to test the stability of fixation using interfragmentary screws of differing sizes. Three-dimensional printing of the same metacarpal fracture enables the replication of the same model morphology and fracture pattern, reducing potential confounding variables associated with differences produced using laboratory osteotomies in cadaver bones and reproduction models. Three-dimensional printing also allowed the printing of numerous repeats of the same model, enabling sample sizes for each group to be calculated with the appropriate statistical power, which has not been done before. The overarching clinical research aim was to assess the influence of screw size on construct

strength. The null hypothesis was that screw size does not influence load to failure.

Materials and Methods

A medical grade computed tomography scan of a 2-part metacarpal spiral fracture in the ring finger of a 45-year-old Caucasian man was segmented using medical imaging software (MIMICS version 19; Materialise). The segmented metacarpal was converted into a 3-dimensional isosurface model and prepared for 3-dimensional printing with data optimization software (3Matic version 11; Materialise).^{13–18} The models were printed in acrylonitrile butadiene styrene (ABS) using a 3-dimensional printer (UPrint SE; Stratasys), with print resolution capable of producing

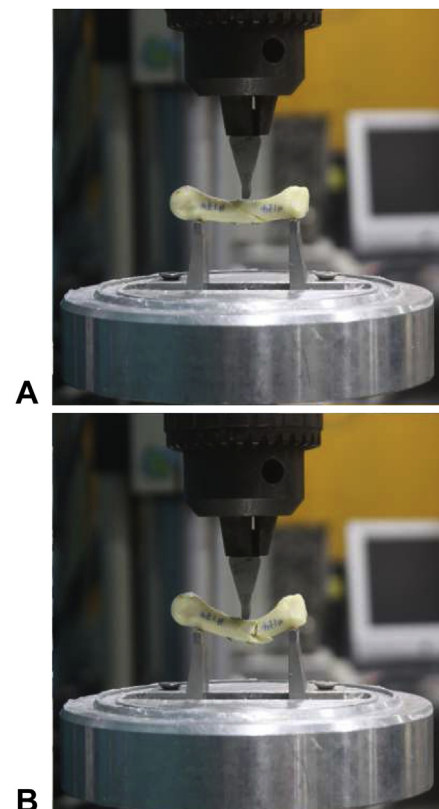


Figure 2. Three-point bend test with an example specimen. A Before testing to failure. B After testing to failure.

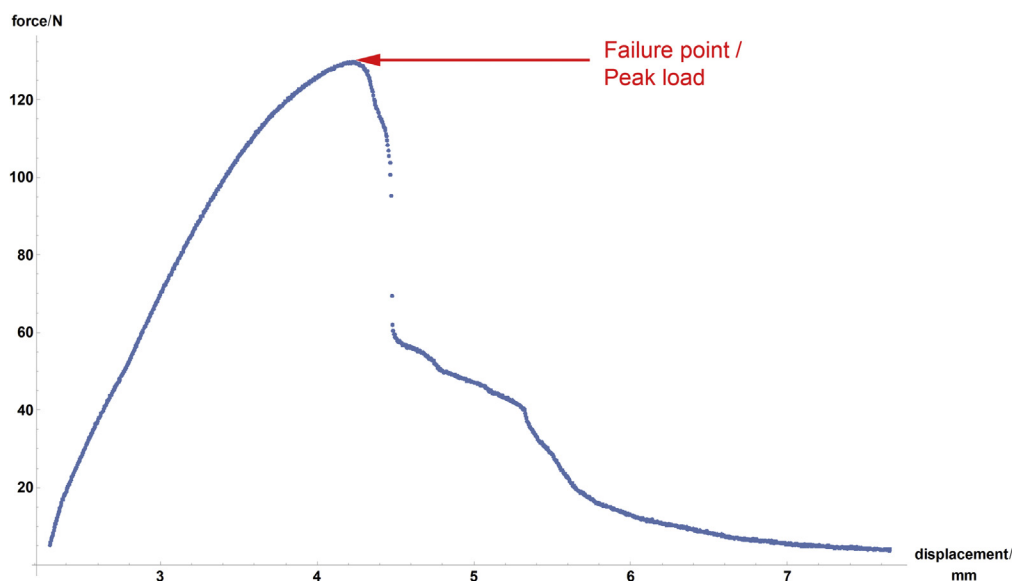


Figure 3. Typical force-displacement curve generated during testing and the failure point (peak load) recorded for analysis.

Table
Summary Statistics for Force Resisted by Constructs Under Three-Point Bending

Screw Size	Group Max	Group Min	Group Mean	Group SD
1.20 mm	170.40	104.20	130.93	17.50
1.50 mm	170.10	84.30	130.50	24.97
2.00 mm	175.10	101.60	137.87	18.44
2.30 mm	167.50	104.30	144.51	17.73

some rudimentary meta-epiphyseal trabecular matrices (Fig. 1). ABS is an opaque thermoplastic polymer with an elastic modulus of 2.1–4 Gpa that is close to that of cortical bone, while not being identical, and much closer than that of metals used for fixation devices.¹⁹

The 3-dimensional-printed models were fixed with 2 cortical screws (Medartis Aptus). Four screw sizes (1.2 mm, 1.5 mm, 2.0 mm, and 2.3 mm) were evaluated. Two bicortical screws of the same diameter were placed across the fracture in vector form as described by Geissler,⁹ evenly spaced, and at least 2 screw head diameters from the diaphyseal fracture line (Fig. 1). Pre-drilling of the screw holes was performed with the aim of replicating a non-lagged standard surgical technique. We used non-lagged screws in our practice as this is supported in both the biomechanical and clinical literature.^{11,12} Pointed-reduction forceps were used to reduce the fracture. As the 2 bone fragments were not attached to each other or to any soft tissue, an additional jig was printed using the 3-dimensional printer to hold the fragments while drilling was performed (Fig. 1). We did not countersink the near cortex of any model as per our current practice in bones of this size. To avoid potential inter-operator differences, a single senior orthopedic surgical resident performed the fixation of all models. A pilot study was performed so that appropriate sample sizes could be calculated using a power analysis. The pilot study demonstrated large variance in peak force values, which was possibly due to the differences between models in screw trajectory. To minimize this, effort was made to drill each model in the main study with the same trajectory. Power analysis summary showed $P = .05$, power of 0.8, and calculated necessary group size (n) equaled 20 per group. Our final testing included 20 models per group. Models in each group were fixed with 2 screws of the same size and same length (e.g., two 1.5-mm diameter screws of 10-mm length). The screws lengths were identical between all models and groups to

prevent this variable impacting the results. However, freehand drilling of screws did mean some screws protruded further through the cortex in some models. All models had bicortical fixation. Four groups were tested: a group with 1.2-mm screw fixation, a second group with 1.5-mm, a third with 2.0-mm, and the final group with 2.3-mm screw diameters.

Models were tested using a servohydraulic testing machine (MTS 858 Bionix; Material Testing Systems) and subjected to an apex dorsal three-point bending protocol (ISO 5628 standard) to failure at 5 mm/min. Data were recorded at 100 Hz. Maximum (peak) load (Newtons, N) was extracted from the load displacement curve for each construct, and the failed constructs were photographed to record the failure pattern (Figs. 2, 3).

Results

All groups were tested for normal data distribution before performing analysis of variance. Analysis of variance with post-hoc Bonferroni hypothesis testing was used to assess whether there were significant differences in the mean failure load between the different screw size groups (SPSS 25; IBM).

No statistically significant differences in peak load between any screw size groups were found (Table). Although there was a trend for higher forces resisted by the larger screws, as can be seen in Figure 4, this did not reach statistical significance. Failure pattern was consistent throughout; the models failed at the screw holes that propagated to the model fracture line (Fig. 5). No models failed because of screw pullout from the ABS material. Occasionally, the model fractured during attempted fixation and before testing. This was mostly observed in the 2.3-mm screw group. Also, pre-testing failures were seen in a small number of 1.2-mm screw models secondary to drill bit fracture while drilling the model due to its inherent small diameter.

Discussion

Our results showed that differing screw sizes did not significantly alter the strength of fixation in these metacarpal models. The current study removed potential variation in bone quality as well as morphology by using the same material (ABS) and identical

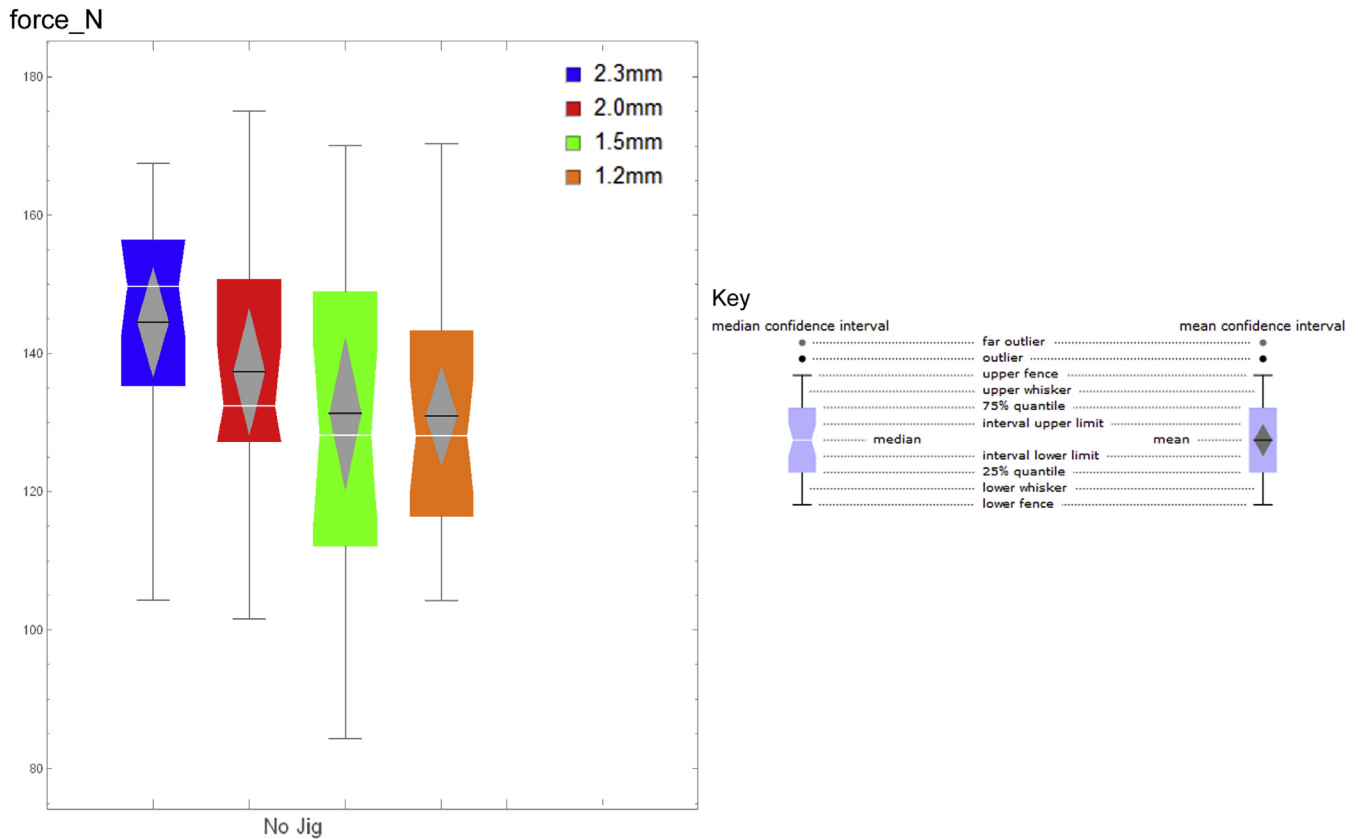


Figure 4. Box plot summaries of resisted peak load during 3-point bending for each screw size showing no significant differences between groups.

geometry based on the computed tomography scan of a single fracture pattern. Clinical studies assessing the screw fixation of metacarpal shaft fractures are rare. In one of the only prospective randomized controlled trials in this field, Horton et al²⁰ compared the fixation of isolated spiral and long oblique proximal phalanx shaft fractures with K-wires to those fixed with 2 interfragmentary 1.5-mm or 2.0-mm lag screws.²⁰ The 28 of 32 patients who completed the trial reported no differences in perceived pain, return-to-work time, clinical deformity, hand grip, and finger pinch strengths at a maximum follow-up period of 15 months. Importantly, the rates of malunion and complications were low and did not differ between groups. Our results similarly showed adequate construct strength in the 1.5-mm and 2.0-mm screw groups, which did not improve with larger 2.3-mm screws using the ABS material and model.

Roth and Auerbach¹¹ highlighted the concerns of intraoperative fracture plus the increased intraoperative time with lagging interfragmentary screws. Thus, they used 1.1-mm to 2.4-mm self-tapping non-lagged bicortical screws. A 100% union rate on average 7 weeks from intervention on x-ray was reported in 37 fractures. Patients were immobilized for a week and received hand therapy and a removable orthosis to promote early range-of-motion. Their complication rate was low and comparable to previous lag screw results from their own practice. The authors concluded that non-lagged bicortical screws were a reasonable alternative to lag screws in metacarpal and phalangeal fractures, and they chose to adopt this method to reduce the rate of fracture during lagging or, in other words, when using larger drill sizes. In our study, we found that the drill holes fractured in some of the 2.3-mm screw group during preparation prior to testing. This correlates with the concerns voiced by Roth and Auerbach¹¹ with respect to drill and screw size in the

bones of the hand. The only models to fail pre-testing were those drilled for 2.3-mm screws as the larger defect had a propensity to propagate to the fracture line prior to screw insertion or during fixation at the point the screw head reached the cortex and compression began. This showed that the drilling itself destabilized the cortical material and this zone of fragility was too close to the fracture line when larger drill bits were used, leading to secondary fracture.

We chose to study bicortical non-lagged screws as our fixation method as this is what we use in our practice and theoretically may lead to less intraoperative time and fracture propagation, while achieving results equivalent to lagged fixation.¹¹ In 2008, Khalid et al²¹ reported pullout strength of bicortical non-lagged versus unicortical 1.7-mm self-tapping screws in 40 cadaveric proximal phalanges. Screws were placed perpendicular to the shaft axis in a dorsal to ventral manner, in both the proximal and distal metaphases and mid-diaphysis. The screws were subjected to increasing static axial pullout forces until failure. They found the fixation of unicortical screws to be statistically inferior to bicortical screws in all 3 regions, but unicortical screws in the diaphysis were superior to bicortical screws in the proximal metaphyseal region. This was attributed to more cortical and less cancellous bone in the diaphysis compared to proximal metaphyseal regions, which may have increased screw purchase in stronger bone. Using bicortical screws in a vector-like manner in our study provided bicortical diaphyseal fixation, maximizing the compression at the fracture and pullout strength. In all the models tested, no model failed because of screw pullout from the ABS material.

Nicklin et al¹² investigated a non-lagged versus lagged construct in 24 cadaver metacarpals with dorso-palmar oblique osteotomies. Using a bow-shaped clamp with built-in drilling guide (Stryker Target Bow) and two 1.7-mm screws aligned perpendicular to the

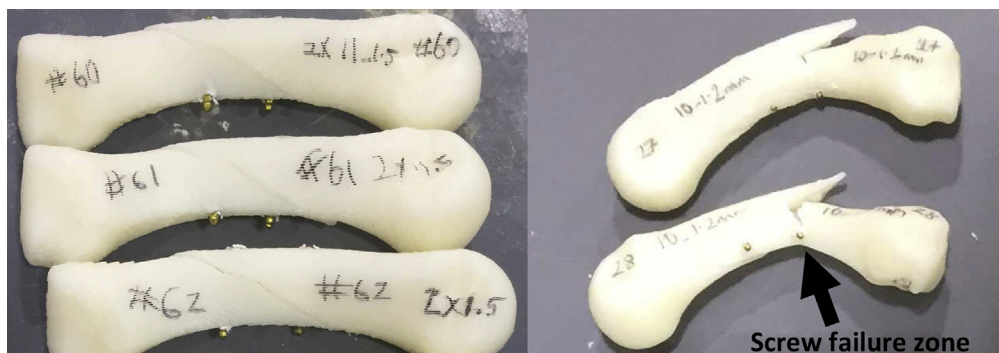


Figure 5. Pre-testing fixed models and post-testing failure patterns for a subsample of the specimens showing that failure occurs consistently at either entry or exit screw hole.

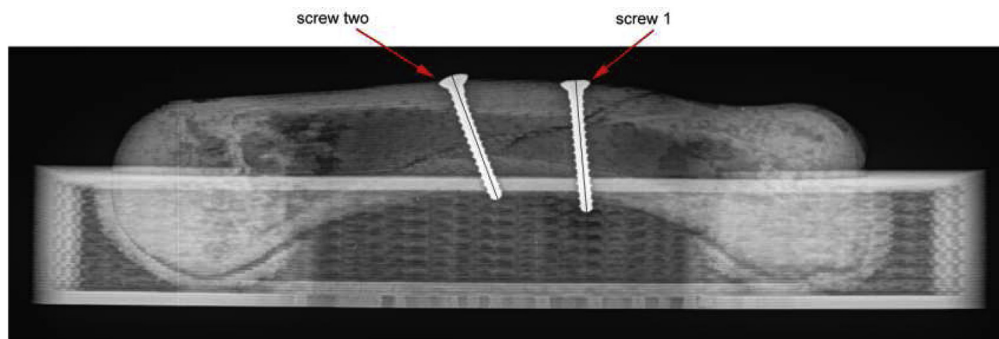


Figure 6. A 1.2-mm screw fracture model is shown in the orthogonal x-ray jig prior to testing. Straight black lines are drawn from the mid-point of the screw tip to the mid-point of the screw head as a visual aid. Screw 2, which is drilled on more of an angle to the bone's dorsal surface than screw 1, shows a greater magnitude of bending.

osteotomy, a cantilever force was applied to the distal metacarpal head. They found no statistically significant difference between the 2 techniques, suggesting that non-lagged bicortical screws were adequate fixation devices in this setting. Liporace et al²² also compared lagged versus non-lagged bicortical screws. Forty-eight cadaver metacarpals were fixed with 1 of 4 screw types: 1.5-mm and 2-mm bicortical and lagged interfragmentary screws. Forty-five-degree oblique osteotomies were loaded to failure in a cantilever-style jig, and their results showed no statistically significant differences between either technique or screw size. The 2.0-mm screws inclined toward higher load failure rates, but it did not reach statistical significance. This mirrored the results in the current study.

Matloub et al²³ compared single 2.0-mm non-lagged compression screws to crossed K-wires, interosseous wires, mini-plates, and cerclage wires with spiral fractures in cadaver metacarpals and proximal phalanges. Their 240 self-cut spiral osteotomies were tested to failure with dorsal apex and volar apex, cantilever bending, and torsional forces. Compression screws showed more rigidity than other techniques and materials in all tests besides proximal phalangeal apex dorsal bending, in which they were equally the most rigid construct with interosseous wires. This provided more support for single interfragmentary compression screws as a fixation choice.

All 4 previously mentioned studies used cadaveric metacarpals and fractures created with osteotomies that inherently added variation to the test samples. Three-dimensional printing and ABS allowed for the same model of a clinical fracture pattern and material, thereby minimizing some of the confounding factors present in cadaveric material studies.²⁴ For example, differences in morphology (size and shape of the bone) and material properties (bone density) were eliminated; however, we also acknowledge

the limitations of this approach in that 3-dimensional-printed polymer models may not accurately reflect in vivo human bone mechanics and fixation within living tissue. Confounding factors with cadaveric material use are common themes highlighted in much of the literature in this field, with clinical studies being a rarity. Cadavers are often available in limited numbers, and statistical power of the results from many of the previously mentioned studies is lacking. Cadaveric bones themselves are often from different fingers with differing sizes, mineral densities, and morphologies. We aimed to eliminate many of these variables with the 3-dimensional-printing approach adopted herein but in doing so we accept the limitations of ABS. However, this is the first study of its kind to reproduce such an accurate true fracture pattern and be able to test it repeatedly with large sample sizes. We also accept that this is a model based on a 45-year-old Caucasian man. This study, therefore, does not account for the breadth of age ranges seen with metacarpal fractures (from young to middle-aged adults, most commonly) and in women. Again, prior research in this field has been limited by these similar issues, with cadaver studies coming from mostly elderly patients of varying ethnicities, often unreported in the literature.

We found a small number of 1.2-mm drill bits bent and fractured during fixation. These drills were thin and prone to bending during eccentric drilling on contact with the surface of the bone model, despite using a drill sleeve. This may have been due to sliding of the drill bit on the surface of the model. This led to damage of the drill bit, which was ideally avoided in clinical practice. We also noted from x-rays of the fixed samples that the 1.2-mm screws were the only screws to bend during fixation (Fig. 6). The x-rays were performed prior to mechanical testing, and Figure 6 shows the bent hardware. Drill fracture and screw bend was only seen in 1.2-mm screw fixation models.

What is clear is that methods used in previous studies vary markedly; screw sizes range from 1.1 mm to 2.4 mm but commonly are 1.5 mm or 2.0 mm. While testing of the samples in the present study showed no difference in fixation strength between groups, we suggest using 1.5- or 2.0-mm screws as there was no significant difference between these 2 screw sizes in fixed construct strength or between these screw sizes and the larger 2.3-mm screw fixed construct strengths. Some 2.3-mm screw models had secondary fractures, suggesting that drilling for a 2.3-mm screw may introduce a significant mechanical defect in the metacarpal bone used in the present study as these are relatively narrow bones (we acknowledge that we did not countersink the near cortex in this trial, which some clinicians routinely perform, and this is a variable not tested in this study). A number of 1.2-mm drill bits snapped, and a number of 1.2-mm screws were bent in the fixed construct.

We agree with Watt et al.²⁵ that a 3-point bending protocol most closely replicates the apex dorsal fracture mechanics and functional loading seen in vivo. However, we also accept that other forces act on the metacarpal, for example, through the actions of the intrinsic hand musculature. Further, the multiplicity of injury mechanisms and associated fracture patterns are not represented in our study. Extending testing with torsional and compression models would also add to our understanding of the suitability of different screw sizes for spiral fracture patterns such as those used herein.

A part of our results, which was perhaps unexpected, was the large variance in construct strength across all screw size groups. We did not control strictly for screw placement and angle during our testing. We chose freehand drilling as this replicated standard practice in the operating room. We debated whether to standardize this variable from the outset. Effects of screw placement and angle are something we plan to investigate in future studies, and the variance seen in our pilot and main testing groups suggests that this may play a significant role in construct strength and warrants further investigation. Our study does not assess fracture union. However, construct stability is known to be a key factor in fracture union. Further clinical studies would be necessary to determine whether the rates of fracture union differ between screw sizes.

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References

1. Adams JE, Miller T, Rizzo M. The biomechanics of fixation techniques for hand fractures. *Hand Clin.* 2013;29(4):493–500.

2. Friedrich JB, Vedder NB. An evidence-based approach to metacarpal fractures. *Plast Reconstr Surg.* 2010;126(6):2205–2209.
3. Day CS. Fractures of the metacarpals and phalanges. In: Wolfe S, Hotchkiss R, Pederson W, Kozin S, Cohen S, eds. *Green's operative hand surgery*. 7th ed. Churchill Livingstone; 2017:231–277.
4. Henry MH. Fractures of the proximal phalanx and metacarpals in the hand: preferred methods of stabilization. *J Am Acad Orthop Surg.* 2008;16(10):586–595.
5. Kozin SH, Thoder JJ, Lieberman G. Operative treatment of metacarpal and phalangeal shaft fractures. *J Am Acad Orthop Surg.* 2000;8(2):111–121.
6. Stern PJ. Management of fractures of the hand over the last 25 years. *J Hand Surg Am.* 2000;25(5):817–823.
7. McNemar TB, Howell JW, Chang E. Management of metacarpal fractures. *J Hand Ther.* 2003;16(2):143–151.
8. Chin SH, Vedder NB. MOC-PSSM CME article: metacarpal fractures. *Plast Reconstr Surg.* 2008;121(Suppl 1):1–13.
9. Geissler WB. Operative fixation of metacarpal and phalangeal fractures in athletes. *Hand Clin.* 2009;25(3):409–421.
10. Kawamura K, Chung KC. Fixation choices for closed simple unstable oblique phalangeal and metacarpal fractures. *Hand Clin.* 2006;22(3):287–295.
11. Roth JJ, Auerbach DM. Fixation of hand fractures with bicortical screws. *J Hand Surg Am.* 2005;30(1):151–153.
12. Nicklin S, Ingram S, Gianoutsos MP, Walsh WR. In vitro comparison of lagged and nonlagged screw fixation of metacarpal fractures in cadavers. *J Hand Surg Am.* 2008;33(10):1732–1736.
13. Parr W, Chamoli U, Jones A, Walsh W, Wroe S. Finite element micro-modelling of a human ankle bone reveals the importance of the trabecular network to mechanical performance: new methods for the generation and comparison of 3D models. *J Biomech.* 2013;46(1):200–205.
14. Parr W, Wroe S, Chamoli U, et al. Toward integration of geometric morphometrics and computational biomechanics: new methods for 3D virtual reconstruction and quantitative analysis of Finite Element Models. *J Theor Biol.* 2012;301:1–14.
15. Tan CJ, Parr WCH, Walsh WR, Makara M, Johnson KA. Influence of scan resolution, thresholding, and reconstruction algorithm on computed tomography-based kinematic measurements. *J Biomech Eng.* 2017;139(10).
16. Mobbs RJ, Choy WJ, Wilson P, McEvoy A, Phan K, Parr WCH. L5 En-Bloc vertebrectomy with customized reconstructive implant: comparison of patient-specific versus off-the-shelf implant. *World Neurosurg.* 2018;112:94–100.
17. Mobbs RJ, Parr WCH, Choy WJ, McEvoy A, Walsh WR, Phan K. Anterior lumbar interbody fusion (ALIF) using a personalised approach: is custom the future of implants for ALIF surgery? *World Neurosurg.* 2019;124:452–458.e1.
18. Wroe S, Parr WCH, Ledogar JA, et al. Computer simulations show that Neanderthal facial morphology represents adaptation to cold and high energy demands, but not heavy biting. *Proc Biol Sci.* 2018;285(1876):20180085.
19. Stratasys. Fused Deposition Modelling Material Properties. Accessed November 23, 2019. <https://www.stratasysdirect.com/materials/fused-deposition-modeling>.
20. Horton TC, Hatton M, Davis TR. A prospective randomized controlled study of fixation of long oblique and spiral shaft fractures of the proximal phalanx: closed reduction and percutaneous Kirschner wiring versus open reduction and lag screw fixation. *J Hand Surg Br.* 2003;28(1):5–9.
21. Khalid M, Theivendran K, Cheema M, Rajaratnam V, Deshmukh SC. Biomechanical comparison of pull-out force of unicortical versus bicortical screws in proximal phalanges of the hand: a human cadaveric study. *Clin Biomech.* 2008;23(9):1136–1140.
22. Liporace FA, Kinchelov T, Gupta S, Kubiak EN, McDonnell M. Minifragment screw fixation of oblique metacarpal fractures: a biomechanical analysis of screw types and techniques. *Hand.* 2008;3(4):311–315.
23. Matloub HS, Jensen PL, Sanger JR, Grunert BK, Yousif NJ. Spiral fracture fixation techniques. A biomechanical study. *J Hand Surg Br.* 1993;18(4):515–519.
24. Dona E, Gillies RM, Gianoutsos MP, Walsh WR. Plating of metacarpal fractures: unicortical or bicortical screws? *J Hand Surg Br.* 2004;29(3):218–221.
25. Watt AJ, Ching RP, Huang JI. Biomechanical evaluation of metacarpal fracture fixation: application of a 90 degrees internal fixation model. *Hand.* 2015;10(1):94–99.