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Biomechanical Comparison of Five Fixation Constructs in a

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Trapeziometacarpal Joint Arthrodesis Model

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13 **Abstract**

14 **Purpose:** Trapeziometacarpal joint (TMCJ) arthrodesis has a high rate of non-union.
15 This biomechanical analysis sought to determine the stiffness of five fixation methods
16 in a TMCJ arthrodesis model.

17 **Methods:** Five fixation constructs were tested in a validated porcine model: crossed
18 1.1 mm Kirschner (K) wires, crossed 1.6 mm K wires, crossed headless compression
19 screws (HCS), compression plating (CP) and locked compression plating (LCP). The
20 cantilever bending stiffness was measured in abduction, adduction, flexion and
21 extension. Samples were loaded to failure in extension. Mode of failure was examined.

22 **Results:** The crossed headless compression screws performed consistently well in all
23 tests. Loading to failure resulted in screw pull-out. In abduction and adduction, HCS
24 and 1.6mm K wires were significantly stiffer than the other constructs. The mean load
25 to failure in extension was similar in HCS, CP and LCP groups (304 N/mm, 311 N/mm,
26 293 N/mm). There were no differences between CP and LCP in any of the
27 biomechanical tests and mode of failure was through plate bending. The crossed 1.1
28 mm K wires performed poorly in all tests.

29 **Conclusions:** Crossed HCS displayed the greatest overall stability. There is no
30 advantage of using a locking plate over a standard plate in compression mode.

31 **Clinical relevance:** The ideal construct stiffness required for successful union after
32 TMCJ arthrodesis is unknown, but HCS provides the most favourable biomechanical
33 environment for construct stability at the arthrodesis site.

34 **Keywords**

35 Arthrodesis, biomechanical, first carpometacarpal joint, fusion, trapeziometacarpal
36 joint

INTRODUCTION

Osteoarthritis of the trapeziometacarpal joint (TMCJ) affects 15% of adults over 30 years and as many as one third of post-menopausal women.¹⁻³ The condition is debilitating, leading to pain and loss of function with reduced dexterity and strength. Non-surgical treatments include activity modification, analgesia, physiotherapy, splinting and steroid injections. If these measures fail to provide adequate relief, surgical options include extension osteotomy, trapeziectomy, arthroplasty and arthrodesis. Several systematic reviews have been unable to establish which surgical option is most effective in the treatment of TMCJ arthritis.⁴⁻⁶

Arthrodesis of the TMCJ maintains the thumb's osseous foundation and transfers axial loading through the scaphotrapezial joint. It compromises on range of motion and pinch precision, but provides a stable painless thumb and is associated with increased grip and pinch strength compared to trapeziectomy or arthroplasty.⁷⁻¹⁰ It has therefore been advocated for high-demand patients such as young manual labourers without concomitant scaphotrapezial arthritis.^{11,12} The procedure was first described by Muller and a variety of fixation methods have since been described to stabilise the arthrodesis site.¹³ Initial techniques involved impaction bone grafting alone with prolonged immobilisation and later progressed to Kirschner wires, tension bands, cerclage wires, screw and staple fixation.¹⁴ Failures, measured in revision rates, are higher than for trapeziectomy +/- ligament reconstruction/tendon interposition but lower than for implant arthroplasty.¹⁵⁻¹⁷ Non-union is a common complication requiring further surgery with reported rates of symptomatic non-union between 6-18%^{10,16,18-25} and radiographic non-union between 7-26%,^{10,20} and no single technique showing superiority.

61 Insufficient stability and compression with resultant excessive motion at an arthrodesis
62 site are recognised risk factors for non-union. Advances in osteosynthesis devices,
63 such as compression screws and locking plate fixations, have provided fixation
64 techniques which confer greater stability and compression.

65 We hypothesised that modern fixation techniques such as compression screws or
66 locking plate fixation produce a more stable construct at the arthrodesis site. Achieving
67 a stiffer arthrodesis construct has the potential to increase clinical fusion rate. This
68 biomechanical study aimed to compare the stability of traditional and modern fixation
69 techniques used in TMCJ arthrodesis. To date, there are no studies comparing the
70 biomechanical properties of traditional versus modern generation fixation implants in
71 a TMCJ arthrodesis model.

MATERIALS and METHODS

Porcine model

Porcine forefoot specimens were used as a model for the human TMCJ. The porcine forefoot model has been validated by several studies for biomechanical research assessing fixation strengths in the hand.²⁶⁻²⁹ A review by the AO Research Institute demonstrates that biomechanical properties of porcine models, including bone mineral density, macrostructure, microstructure and bone composition make the porcine model a subject of choice for orthopaedic research studies.³⁰ The central carpal bone of a porcine forefoot is similar to the human trapezium in its size and saddle-like shape. It has previously been validated for modelling surgical intervention on the human TMCJ in the context of biomechanical studies.³¹

All animals were of the same race, free from medical co-morbidities and six months old at the time of euthanasia. Skeletal maturity was confirmed by demonstration of closed physes on plain film radiography.

Surgical preparation

Five fixation methods were assessed with five specimens per method, resulting in a total of 25 samples. The samples were dissected to isolate the central carpal bone, or 'model trapezium', and associated metacarpal. All ligament/soft tissue attachments were dissected off the bones. The joint surfaces and subchondral bone were then excised resulting in a chevron shape, replicating a published technique for TMCJ arthrodesis to increase the intrinsic stability at the arthrodesis site.³² All procedures

were performed by a senior fellow in hand surgery (RS) after completion of specialist training.

The specimens were fixed using one of the following techniques: Crossed 1.1 mm K wires (Series 1), crossed 1.6 mm K wires (Series 2), crossed headless compression screws (Series 3), compression plating (Series 4), locked compression plating (Series 5), as illustrated in Figure 1. All materials were supplied by Zimmer Biomet (Zimmer GmbH, Switzerland). The fixation methods were selected based on a literature review of published techniques for TMCJ arthrodesis at the time of writing identifying 31 relevant publications (supplementary table S1) and represent the most commonly reported techniques (K wires) as well as those contemporary techniques with the most promising published outcomes (HCS, CP, LCP).

Series 1 and 2 were compressed manually and transfixed with bicortical K wires in a crossed configuration. In Series 3, 3 mm diameter cannulated headless compression screws were placed in a crossed configuration with cancellous purchase within the trapezium and cortical purchase in the metacarpal shaft. Series 4 and 5 were both fixed using 2.5 mm 'Y' plates which were cut to leave 7 holes. The arthrodesis site was compressed through the plate. Series 4 was fixed with 2.5 mm non-locking cortical screws and Series 5 with 2.5 mm locking screws. All screws achieved bicortical fixation. Plates were pre-bent to fit the anatomy of the bone, as is performed in clinical practice. However, it was noted that there was gapping on the volar side of the joint despite pre-bending. This gapping was left uncorrected to replicate the normal clinical scenario.

The samples were fixed into a custom-made jig using polymethylmethacrylate bone cement augmented with transfixing orthogonal K wires (Figure S1). The dorsal surface

acted as the reference for the K wires and the direction of the applied forces. The model trapezium was fixed to the base unit and the metacarpal was attached to the testing machine.

Loading sequence

Samples were tested in two planes by an Instron 5565 (Norwood, Massachusetts) materials testing machine loading at a rate of 0.05 mm/sec. Cantilever bending stiffness was measured in abduction and adduction, and then samples were rotated through 90° and tested in flexion and extension. The applied load was determined in pilot studies and the maximum load was maintained below the value that was observed to cause permanent deformation. Subsequently, all samples were loaded to failure in extension, as this is the direction of the force on the TMCJ during pinch grip.³³ Increasing cyclical loads of 100 N increments were applied to the metacarpal until failure occurred. The samples were then examined macroscopically to determine the mode of failure. The outcome measures were stiffness of construct, load to failure, and mode of failure.

Statistical analysis

We performed an a priori power calculation using an independent data set with similar study methodology.³⁴ Based on this, a sample size of four specimens was required for each group in order to demonstrate superiority of a continuous outcome with a power of 80% (1 – beta) and a significance level of 5% (alpha). To account for the unknown

140 stiffness provided by modern fixation techniques, which had not been tested in the
141 literature to date, we decided to use five samples per fixation method.'

142 A one-way ANOVA test was used to assess for significance, assuming a p-value of
143 0.05. Where group differences were significant, post-hoc analysis was performed
144 using Tukey's method. Figures for each series are expressed as mean +/- Standard
145 Deviation.

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RESULTS

Stiffness

In both abduction (Figure 2) and adduction (Figure 3) the 1.6 mm K wires and HCS were the stiffest constructs. The difference within each group was statistically significant (one-way ANOVA: Abduction $p < 0.01$; adduction $p = 0.01$). Tukey's post hoc test showed these constructs were both independently significantly stiffer than the other three fixation methods. No significant differences were evident between fixation methods when testing stiffness in flexion (Figure 4) and extension (Figure 5) below load to failure forces.

Load to failure

Both fixation methods utilising K wires performed poorly in 2 mm deformation tests (Figure 6), failing at a mean 163.8 ± 61.4 N/mm and 228.3 ± 50.1 N/mm for 1.1 mm K wires and 1.6 mm K wires, respectively. The remaining three methods performed similarly well. The results for this group showed statistical significance ($p = 0.03$). Post hoc analysis revealed this to occur between the 1.1 mm K wires group and both HCS & CP.

There was no statistically significant difference in load to failure between the two methods of plate fixation.

Mode of failure

168 The mode of failure (Table 1) was consistent for each of the fixation methods. In three
169 of the LCP specimens the screw just distal to the osteotomy site disengaged from its
170 locking hole prior to plate bending occurring. There was no associated change in the
171 load to failure curve and the other locking screws remained engaged, so this was not
172 deemed to be the mode of failure.

DISCUSSION

When arthrodesis of an arthritic TMCJ is performed, a rigid construct is required to maintain adequate alignment during the postoperative healing period while bony union is awaited. Considerable TMCJ loading with associated motion at the arthrodesis site occurs even with relatively small forces from everyday activities such as during key pinch.³⁵ Stiffer fixation methods may therefore maximise the chance of avoiding non-union, fixation failure, revision surgery and ongoing morbidity. This biomechanical study sought to identify the stiffest TMCJ arthrodesis construct in a validated porcine model to allow surgeons to choose the most suitable fixation technique.

Only one previous biomechanical study has compared the stiffness of TMCJ arthrodesis techniques.³⁴ Stokel et al used combinations of cerclage wires and K wires to fix the arthrodesis site. Of the studied fixation constructs, the tension band wire provided the greatest stability in torsion, whereas cerclage wiring fixations were stiffest in adduction/abduction and flexion/extension testing. High rates of re-operation to remove prominent hardware and the introduction of modern generation implants have led to a decline in the use of these fixation methods.

Given the current paucity of biomechanical evidence assessing the TMCJ, comparing our results with those of biomechanical studies assessing stability of fixation constructs in other anatomical locations provides external validity to our findings. In an evaluation of five fixation devices for proximal interphalangeal joint fusion, Capo et al demonstrated that an intramedullary linked screw had significantly greater stiffness than wiring or dorsal plating constructs.³⁶ In a cadaveric metacarpal neck fracture model, Avery et al found that peak load to failure was significantly higher in headless

compression screws than crossed K wires in 3-point bending and axial loading.³⁷ When comparing plate versus crossed screws in a study on radial neck fractures, Chen et al concluded that crossed screws were stiffer and failed at significantly higher loads.³⁸ Another study of radial neck fracture fixations using 1.6 mm K wires against 2.4 mm non-locking and locking 'T' plates found no difference in stiffness amongst the three constructs when undergoing the same mechanical bending tests used in our study. However, when an additional interfragmentary screw was applied through the plate, the construct stiffness increased by 57%.³⁹ When comparing the stiffness of constructs used for first metatarsophalangeal joint arthrodesis, Politi et al reported that the bending moment of crossed K-wires was comparable to dorsal plating. When an additional single inter-fragmentary screw was applied the stiffness increased 12-fold.⁴⁰ This phenomenon can be explained when examining the stability of fixation devices in the context of the neutral axis of a bone. Despite the stability provided by fixed-angle constructs of modern locking plate fixations, these off-axis fixations are inherently less stable than on-axis devices. This is in keeping with previously published work and explains why crossed HCS and crossed 1.6 mm K wires have performed well in our study.

Our study consistently demonstrated that there is no difference in stiffness and failure between locking and non-locking plate constructs. This is in keeping with conventional use of locking plates where their benefits are primarily in osteoporotic bone. Doht et al reached a similar conclusion when comparing locking vs. non-locking fixation of metacarpal fractures in a porcine model,⁴¹ and Trease et al had similar results in a

cadaveric model of distal radius fractures.⁴² Hence, the increased cost of using locking plates is not justified.

In TMCJ arthrodesis, the plate is applied to the dorsal surface of the joint, which represents the compression side during an extension moment. Biomechanically, plate placement on the tension side would be more robust. Due to anatomic constraints, however, this is not feasible at the TMCJ. An extension moment therefore produces gapping at the arthrodesis site rather than compression. This is what we observed during our experiment and has also been observed in the foot previously.^{43,44}

Over the last decade, several other novel fixation techniques for TMCJ arthrodesis have been described with promising early results. Their clinical use is not currently widespread and they were not included in our analysis. The addition of a screw across the arthrodesis site when using plate fixation is a simple way to significantly improve stability. Pflibsen et al reported no cases of non-union among 22 of TMCJ arthrodeses when a T-plate fixation was augmented with a single oblique interfragmentary screw.⁴⁵ Doht et al reported that quadrilateral plates could resist 75% more load to failure when compared to standard plates of similar length.⁴¹ Quadrilateral plates also have promising early clinical results, including when compared to trapeziectomy.^{10,46} Vanderzanden et al used intramedullary locking devices in a case series of 17 TMCJ arthrodeses and reported that all patients achieved bony union and required only short periods of immobilisation.⁴⁷ These devices behave similarly to crossed HCS and act as true on-axis fixations.

Our study has some limitations. This was an *in vitro* study where the surrounding soft tissue stabilisers were compromised and not accounted for in the final stiffness measurements. The porcine model acts only as a surrogate for human bone, and while no difference existed between race or age of our specimens, individual bone quality was not formally assessed. We tested a simplified model of the arthrodesed TMCJ biomechanics by loading in two planes of motion when in fact more complex, composite forces exist in physiological thumb movement. Minor volar gapping observed with plate fixations may be addressed with adjuncts such as bone graft in the clinical setting, but maintaining identical experimental methods when testing different fixation constructs meant that adjunctive techniques to overcome technical challenges were not permissible. Low load cyclical testing may also be of value in testing for fatigue failure of each construct.

Finally, the precise mechanisms underlying the high non-union rate for arthrodesis of this joint are poorly understood and we accept that many factors other than the degree of construct stiffness affect the likelihood of union in the clinical setting. Achieving stronger compression at the arthrodesis site may not only improve intrinsic construct stiffness, but also promote union through an enhanced biological healing and remodelling response *in vivo*. Local factors such as blood supply also a key role, as demonstrated by successful revision of TMCJ non-union using vascularised bone graft.⁴⁸ Further aspects such as duration of K wire stabilization,⁴⁹ use of bone graft⁵⁰ and the quality of joint preparation⁵¹ have also been highlighted. These factors are beyond the scope of our biomechanical *in vitro* study and warrant further research.

266 While our study shows that crossed headless compression screws were the stiffest
267 construct overall, and locking plates had no advantage over standard plates, this
268 biomechanical data should serve as a baseline to guide further biomechanical work
269 assessing other fixation techniques and comparative clinical studies focusing on which
270 fixation method has the highest union rate and best functional outcome.

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Figure Legends

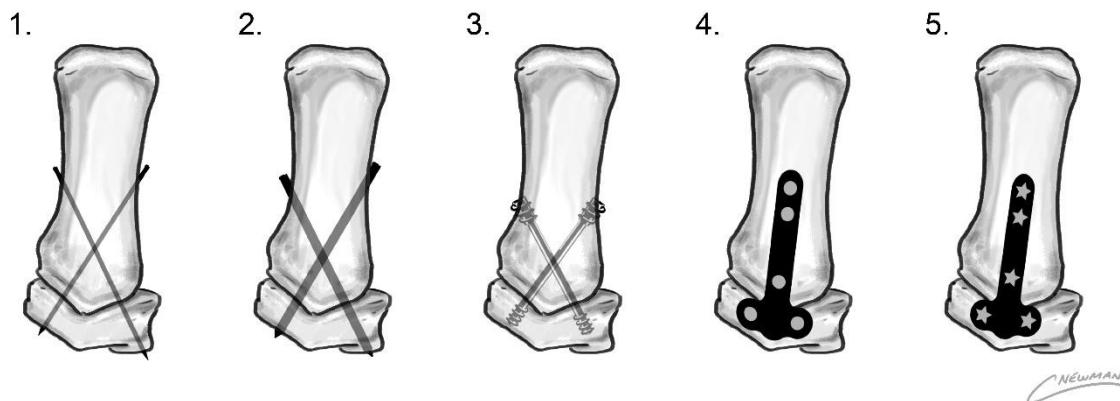


Figure 1. Five fixation methods used for this study.

The five fixation methods tested: Series 1- crossed 1.1 mm K wires, Series 2 – crossed 1.6 mm K wires, Series 3 – crossed headless compression screws, Series 4 - compression plating, Series 5 - locked compression plating

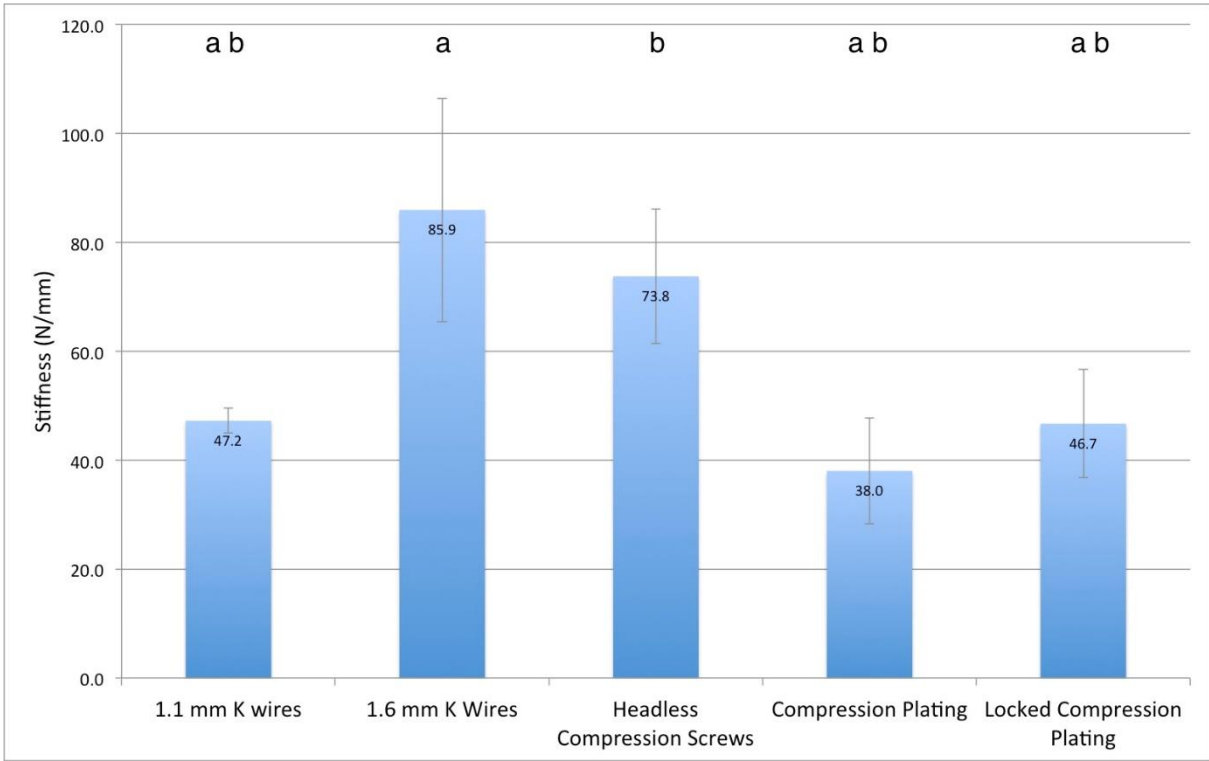


Figure 2. Mean stiffness of each construct in abduction.

Grouped letters denote significance ($p < 0.05$) between constructs.

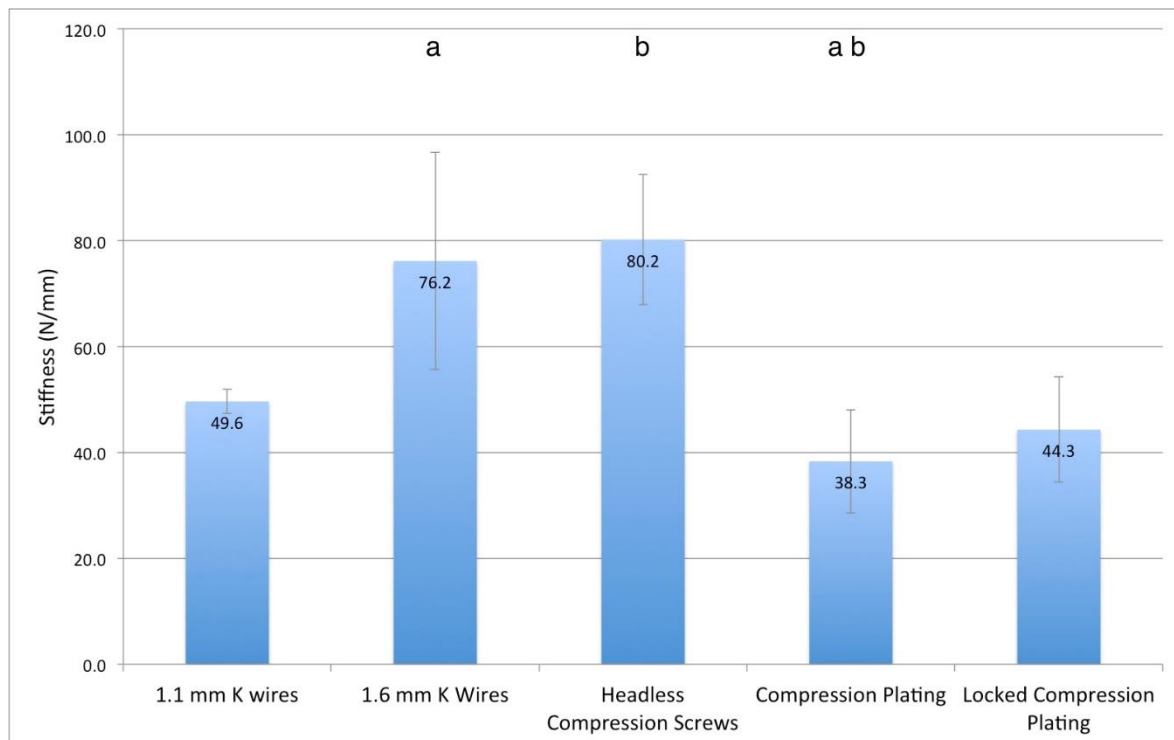


Figure 3. Mean stiffness of each construct in adduction.

Grouped letters denote significance ($p < 0.05$) between constructs.

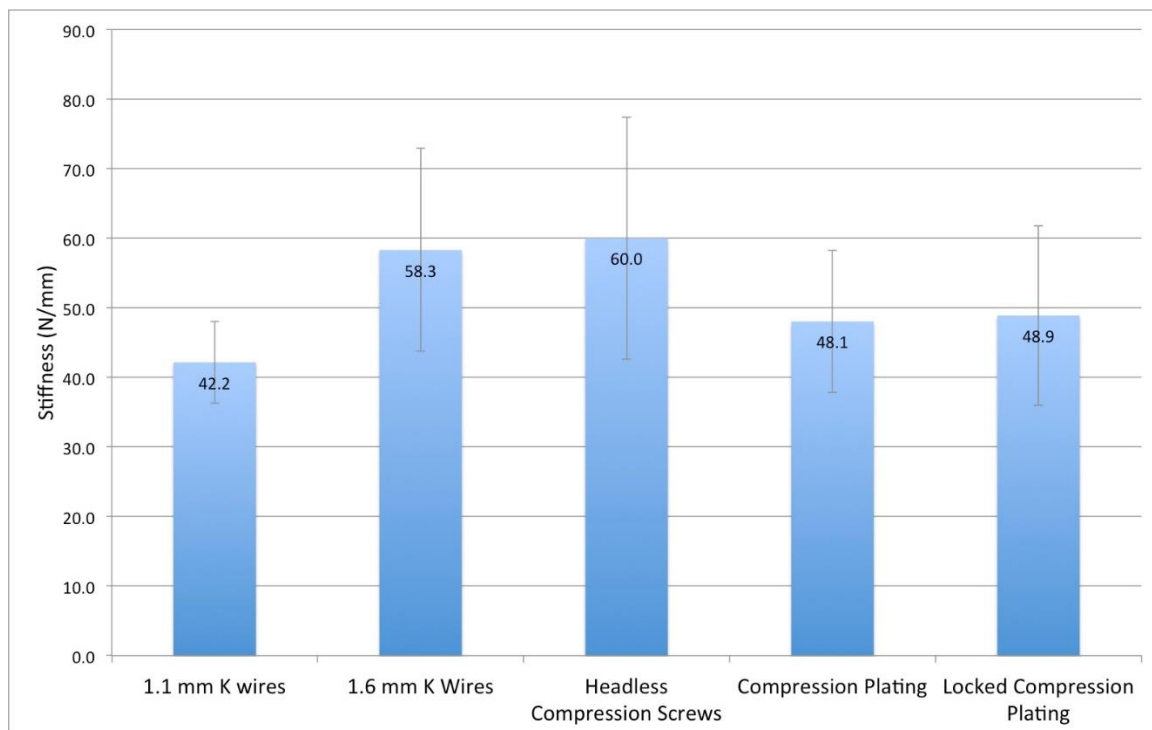


Figure 4. Mean stiffness of each construct in flexion.

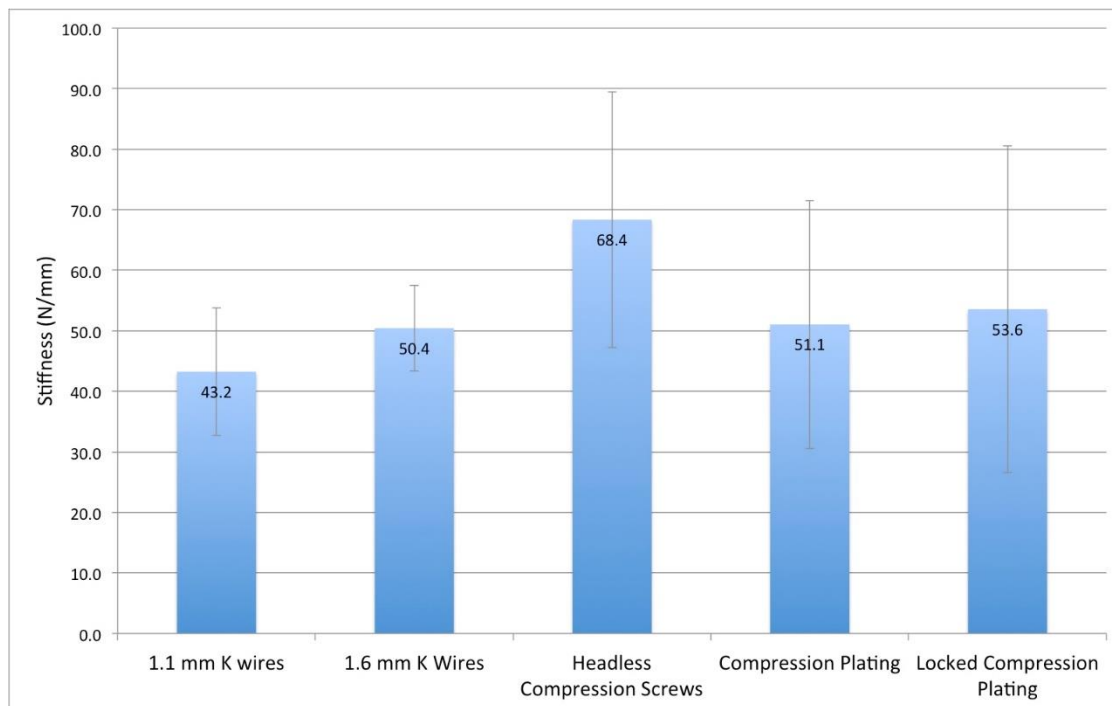


Figure 5. Mean stiffness of each construct in extension.

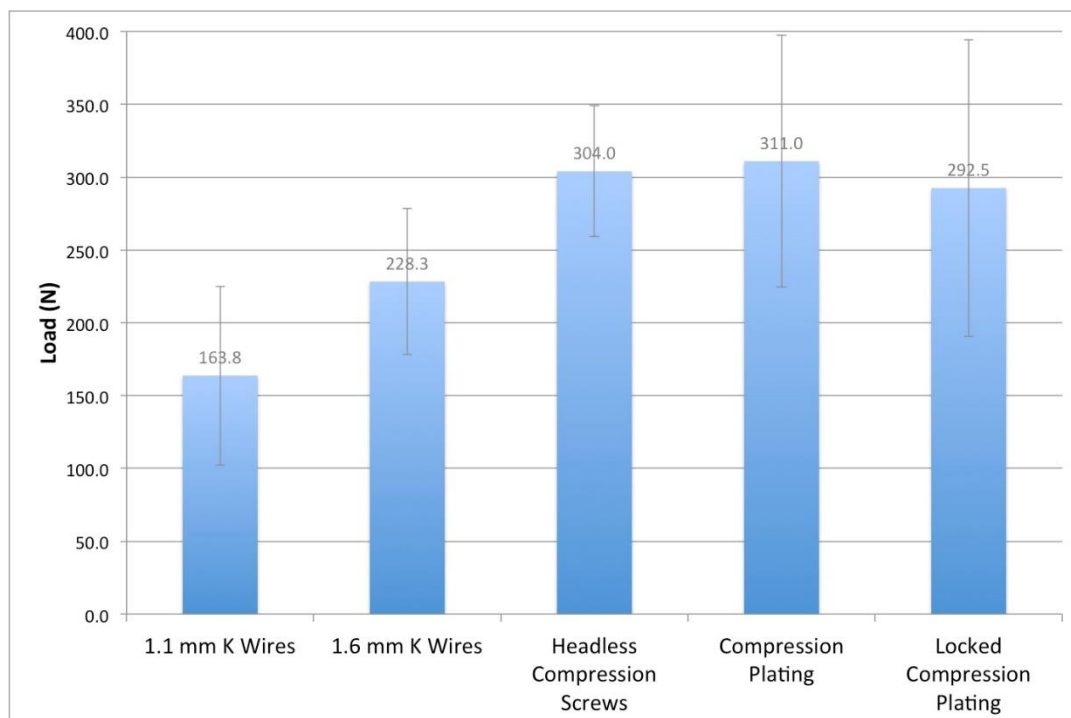


Figure 6. Mean load required to produce 2 mm permanent deformation of each construct.

Grouped letters denote significance ($p < 0.05$) between constructs.

Fixation Method	Mode of failure
1.1mm K Wires	Wire pull out
1.6mm K Wires	Wire bending
Headless Compression Screws	Screw cut out in the trapezium/bone failure
Compression Plating	Plate bending
Locked Compression Plating	Plate bending

Table 1. Mode of failure for each fixation method

Supplementary material

Table S1. Literature review of published TMCJ arthrodesis fixation methods

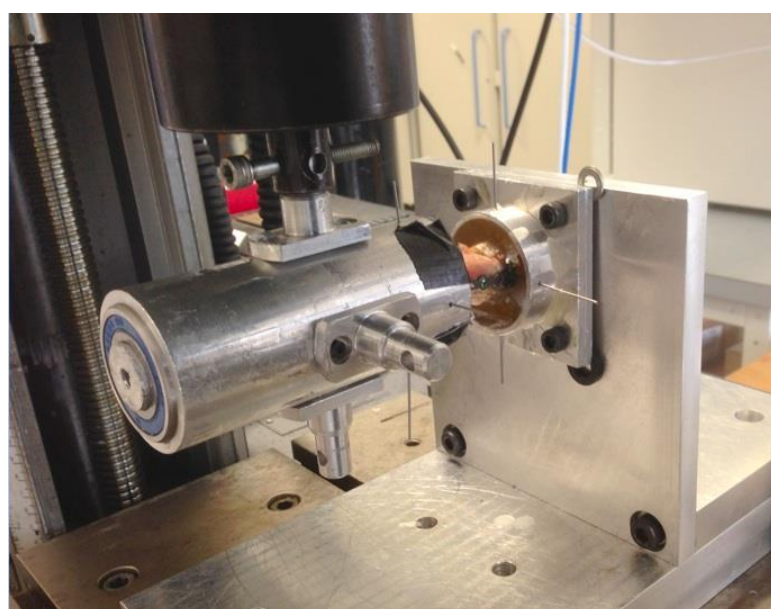


Figure S1. Photograph of experimental setup

Experimental setup showing (right) trapezium fixed to base unit, (left) metacarpal attached to testing arm of the Instron materials testing machine.