Hand Surgery and Rehabilitation 38 (2019) 307–311

Available online at ScienceDirect www.sciencedirect.com

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Original article

Proximal interphalangeal joint arthrodesis using a compression wire: A comparative biomechanical study

Arthrodèse de l'articulation interphalangienne proximale par un fil de compression : étude comparative biomécanique

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A R T I C L E I N F O

Article history:
Received 2 November 2018
Received in revised form 28 May 2019
Accepted 21 July 2019
Available online 2 August 2019

Keywords:
Interphalangeal arthrodesis
Compression wire
Intraosseous wiring
Biomechanical study

A B S T R A C T

Arthrodesis of the proximal interphalangeal joint is a proven technique for treating of a range of pathological conditions, including osteoarthritis. There are multiple surgical procedures. A biomechanical study was conducted to compare the stability of a compression wire to intraosseous wiring for the arthrodesis. Seventeen formalin-fixed human fingers were randomly assigned into two groups and the bone mineral density was determined. Arthrodesis in 20° flexion was performed using an oblique compression wire ($n = 8$) or intraosseous wiring ($n = 9$). The stability of the arthrodesis was tested by applying a tensile bending force until failure. The mean force needed to fail the compression wire arthrodesis and intraosseous wire arthrodesis was not significantly different (76.2 N, SD 31 N and 63.0 N, SD 28 N). There was no correlation between bone density and force to failure. The compression wire was within the approximate range achieved by intraosseous wiring in withstanding substantial force before failure. From a biomechanical point of view, a compression wire is feasible for PIP arthrodesis.

Mots clés :
Arthrodèse de l'articulation interphalangienne proximale
Fil de compression
Brochage intra-osseux
Étude biomécanique

R É S U M É

L'arthrodèse de l'articulation interphalangienne proximale est une technique éprouvée pour le traitement de nombreuses indications pathologiques, comme l'arthrose. Différentes techniques chirurgicales sont utilisées. Pour en démontrer l'applicabilité, une étude biomécanique a été menée, dans laquelle on a comparé la stabilité d'un fil de cerclage en compression avec une fixation intraosseuse pour l'arthrodèse. Dix-sept doigts fixés dans une solution de formaldéhyde ont été assignés par hasard à deux groupes. La densité minérale osseuse a été mesurée. L'arthrodèse en flexion à 20° a été effectuée par fil de cerclage en compression ($n = 8$) et par fixation intraosseuse ($n = 9$). La stabilité de l'arthrodèse a été testée par l'application d'une force d'extension jusqu'à la rupture. La force moyenne dont on a eu besoin jusqu'à la rupture du fil de compression-arthrodèse et de l'arthrodèse intraosseuse n'a pas été très différente (76,2 N, SD 31 N et 63,0 N, SD 28 N). Il n'y a pas de corrélation entre la densité osseuse et la force de rupture. Les résultats des fils de cerclage en compression sont approximativement du même ordre que les fixations intraosseuses en ce qui concerne la force appliquée avant rupture. Pour cette raison le fil de cerclage compression pourrait être considéré d'un point de vue biomécanique pour l'arthrodèse.

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https://doi.org/10.1016/j.hansur.2019.07.002
2468-1229/

1. Introduction

Since the 1940s, arthrodesis of the proximal interphalangeal (PIP) joint has been a proven procedure for the treatment of a range of pathological conditions [1]. The PIP joint is fused at angles from 15–45°, depending on the finger affected [2]. Although one can achieve reasonable results with different techniques, the degree of compression and stability necessary to achieve rapid bone union is an unresolved issue [3–5].

This biomechanical study features an implant – a compression wire – that is manufactured and distributed by Koenigsee Implantate GmbH (Allendorf, Germany). The compression wire is a modification of the K-wire and has been successfully used previously for percutaneous fixation of simple cross and short angled fractures of the proximal and middle phalanges and for scaphoid fractures [6,7]. Consistent with the principle of headless compression screws, it is equipped with two threads of different pitches and separated by a variable threadless section. The diameter varies from 1.0 mm at the tip to 1.8 mm at the second thread. The compression wire is installed with a 50 mm positioning-tip (Fig. 1). The threads and main part of the compression wire apply compression at the joint line. The different thread pitches cause a convergence of the two bones of 0.33 mm per rotation [6]. In a clinical application, the wire would be cut at both ends and buried subcutaneously. After bony fusion is confirmed and the implant could be removed through a small incision if symptomatic.

To prove feasibility, a biomechanical study was conducted in a cadaver model comparing the stability of a compression wire to that of intraosseous wiring as described by Lister [8]. Intraosseous wiring was chosen as a reference procedure since it is a well-established technique for arthrodesis of the finger joints and fractures of the phalanges [3,8–11].

2. Material and methods

Seventeen formalin-fixed human cadaver fingers, all separated from the hand and from different specimen, were randomly assigned to two groups and tested to failure in tensile bending in a parallel group design. In the first group ($n = 8$), PIP joint arthrodesis was performed using a single oblique compression wire, while in the second group ($n = 9$), the joints were fused by intraosseous wiring according to Lister [8]. A standardized angle of 20° flexion was used to provide better comparability with the existing literature on PIP joint arthrodesis. The angle was set using a customary finger goniometer.

The specimens were separated at the metacarpal and distal interphalangeal joint and all soft tissues were removed except the collateral ligaments. No articular cartilage was removed nor was the head of the proximal phalanx and base of the middle phalanx molded, similar to the pepper-pot method [12].

Before conducting the failure tests, the bone mineral density of each specimen was measured by dual energy X-ray absorptiometry (Prodigy®, GE Healthcare GmbH, Solingen, Germany) to determine whether there was a correlation between bone mineral density and biomechanical stability. To avoid exclusion bias, no specimens were left out due to their mineral bone density.

A compression wire with a 10-mm threadless section was used. Arthrodesis with the compression wire was achieved with three turns of the trailing thread inserted into the cortical bone. The wire was inserted 8 mm proximally from the arthrodesis site in a radio-ulnar plane crossing the joint at 45°angle (Fig. 2). For intraosseous wiring, an 0.8 mm cerclage wire and 1.0 mm K-wires were used (Fig. 3). All implants were made of medical stainless steel.

Tests were run in a four-point bending setup using a universal testing machine (Zwick Z050®, Zwick GmbH and Co. KG, Ulm, Germany) at room temperature. For the specimen to fit better in the specimen holder, the base of the proximal phalanx and the head of the distal phalanx were embedded in cylinders of cold polymerized plastic (Technovit 4027®, Heraeus Kulzer GmbH, Wehrheim, Germany). Cylindrical embedding was chosen because it allows compensation movements and provides steady seating while loading. The force conductor features two arms that were 6 mm apart from each other and placed 3 mm proximally and distally from the arthrodesis site on the specimen (Fig. 4). No preloading was applied. Force was applied and recorded continuously at a rate of 100 mm/min in tensile bending (as expected in accidental trauma) until failure occurred. Failure was defined as more than 15% loss of applied force relative to the previous measurement point resulting in an immediate, automatic force cut-off (Fig. 5). The force required was detected by a computer using testXpert II® software (Zwick GmbH and Co. KG, Ulm, Germany).

Statistical evaluation was carried out using Student's *t*-test for normally distributed data and independent samples having equal variances. The data were normally distributed according to Shapiro-Wilk-test.

This study was approved by our institutional review board (reference number: BB 130/13).

3. Results

Although the mean maximum force of the compression wire (76.2 N, SD 31 N) was superior to intraosseous wiring (63.0 N, SD 28 N), the difference was not statistically significant ($P = 0.373$).

The average bone mineral density in the group of specimens fused by intraosseous wiring was 0.256 g/cm^2 as compared to 0.287 g/cm^2 in those fused by a compression wire. There was no correlation between bone density and stability for either of the two techniques. Thus, there was no evidence of superiority of either technique when used for arthrodesis of bones with low bone mineral density ($P = 0.360$).

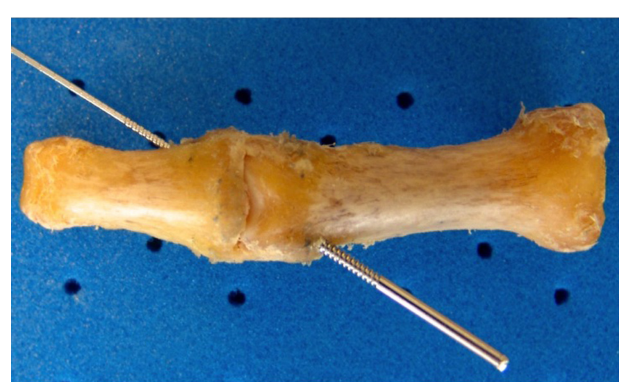

Fig. 2. Photograph of proximal interphalangeal joint arthrodesis using the compression wire.

Fig. 1. Photograph of the compression wire's different pitches and the threadless section.

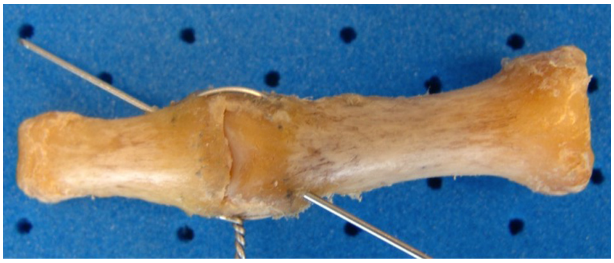

Fig. 3. Photograph of proximal interphalangeal joint arthrodesis using intraosseous wiring.

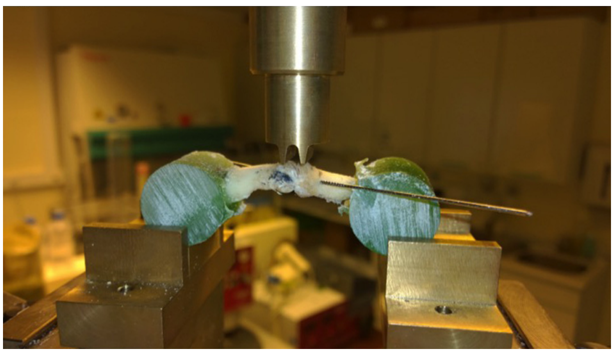

Fig. 4. Photograph of the testing jig during a test of the compression wire.

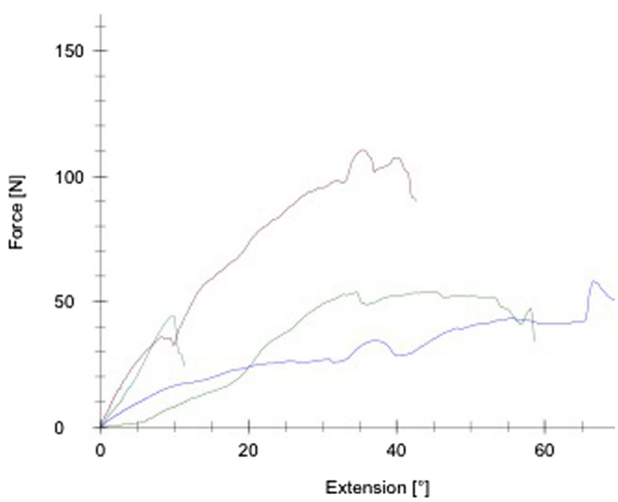

Fig. 5. Example of the curves of four tested specimen fused with the compression wire with the corresponding load values [N]. Although a tensile load was applied in bending at a constant speed of 100 mm/min, the curves do not show a linear development. The drop in the curves corresponds to the occurrence of defined loss of stability, which was defined as failure and the test was automatically stopped.

4. Discussion

The primary objective was to test whether a compression wire has superior biomechanical strength compared to intraosseous wiring in tensile bending, as this would be the loading direction during most traumas. The findings provide no definitive answer as to whether a compression wire is better suited for PIP joint arthrodesis than an intraosseous wire if biomechanical strength is the decisive factor [3,13].

Only a few biomechanical studies have compared the stability of different techniques for PIP joint arthrodesis.

Most recently, Alluri et al. compared traditional 90/90 intraosseous wiring to 90/90 intraosseous wiring augmented with two headless cannulated screws and found no significant differences when loading to catastrophic failure [14]. Capo et al. compared a new intramedullary linked screw with intraosseous wiring, tension band wiring, 90/90 intraosseous wiring and dorsal plate arthrodesis and, amongst others, tested maximum extension. With an average ultimate strength of 21 $\pm$ 8 N, the intramedullary linked screw proved significantly superior to all other techniques except intraosseous wiring. However, since the ultimate strength of the intramedullary linked screw was far below the strength determined in current study for the compression wire and intraosseous wiring, the results cannot reasonably be compared [3]. Kovach et al. compared the ultimate strength of two different types of intraosseous wiring – two crossed K-wires and tension band wiring – in flexion bending. Although not statistically significant, tension band wiring was the strongest, followed by intraosseous wiring [9]. Ayres et al. compared the Herbert screw to tension band wiring. They showed superior stability but the results were not statistically significant [15]. When compared to arthrodesis by power-driven staples, as done by Ritt and Bos, tension band wiring proved superior and reached statistical significance [5]. The same results – superiority of tension band wiring – were found when comparing it to a threaded tension band using resorbable sutures [16].

It is important to note that different rates of loading were used in the above studies. In accordance with Ayres et al. and Mittelmeier et al., the load was applied at 100 mm/min in our study [15,16]. In contrast, Capo et al., Ritt and Bos, Kovach et al., as well as Alluri et al. used far slower rates, ranging from 0.6 to 5.1 mm/min [3,5,9,14]. While the stability of stainless steel decreases with increasing loading rates under in vitro conditions, the results of current biomechanical studies on PIP joint arthrodesis were not altered by this correlation [17]. All studies are summarized and compared in Table 1.

After testing, each specimen in our study was checked for potential effects of testing. Breakage of a K-wire, cerclage or compression wire did not occur in any technique. Nevertheless, there were some visual differences between the two techniques. Permanent deformation of the compression wire was mostly limited to the threadless section and the specimen showed only moderate bony damage. Specimens fused by intraosseous wiring often exhibited major bone destruction because the cerclage wire cut through the bone, and there was also loosening of the wire loop and migration of the K-wire.

With respect to bony destruction and the failure mechanisms, we assume the compression wire failed when both threads lost their cortical hold, resulting in a significant loss of stability (Figs. 6 and 7). A possible explanation for the more severe bony destruction found with intraosseous wiring might be that the pre-existing damage occurring during placement is more complex. Due to its larger diameter, the compression wire's optimal placement should be achieved on the first pass because repositioning can cause significant damage to the bone and might impair secure cortical seating. Moreover, after failure occurred and the bending force was released, the intraosseous wiring specimen often remained displaced, unlike the specimens with the compression wire, where after release, they remained set virtually in the arthrodesis position. Interestingly, this observation matches those reported by Kovach et al. when comparing intraosseous wiring and K-wires [9].

Our study has certain limitations. As previously pointed out by some authors, biomechanical testing to failure creates forces on the PIP joint well above those generated by most daily activities (1.9 to 19.4 N). Although some activities exceed the strength of both the compression wire and intraosseous wiring, such as

Table 1
Summary of published biomechanical studies on proximal interphalangeal joint arthrodesis in which the load to failure was tested.

Authors and year	Technique	Angle of fusion [°]	Direction of loading	Loading rate [mm/min]	Specimen	Maximum load recorded	
						[N]	[Nm]
Vonderlind et al. (current study)	Compression wire	20	Extension	100	Human, formalin	76.20 ± 11.07	1.52 ± 0.22
	Intraosseous wiring					63.00 ± 9.31	1.26 ± 0.18
Kovach et al. [9]	Intraosseous wiring, type I	30	Flexion	5.1	Human, formalin	n/a	0.74 ± 0.39
	Intraosseous wiring, type II						0.35 ± 0.14
	Crossed K-wires						0.69 ± 0.18
	Tension band wiring						1.22 ± 0.43
Ayres et al. [15]	Herbert screw	n/a	n/a	100	Human, formalin	200 ± 127.48	n/a
					Human, fresh frozen	174.55 ± 97.08	
	Tension band wiring				Human, formalin	147.09 ± 39.22	
					Human, fresh frozen	185.34 ± 113.75	
Ritt and Bos [5]	2 staples, 10 × 10 mm	30	Flexion	3.18	Human, formalin	n/a	0.61 ± 0.13
	3 staples, 7 × 7 mm						0.56 ± 0.19
	Tension band wiring						0.90 ± 0.28
Mittelmeier et al. [16]	Tension band with PDS suture	20	Flexion	100	Human, formalin	n/a	8.1 ± 3.5
					Human, fresh frozen		7.4 ± 3.7
	Tension band wiring				Human, fresh frozen		12
Capo et al. [3]	Intramedullary linked screw	25	Extension	0.6	Human, fresh frozen	21 ± 8	n/a
	Intraosseous wiring					n/a	
	Dorsal plate						
	90/90 intraosseous wiring						
Alluri et al. [14]	90/90 intraosseous wiring	30	Extension	0.6	Human, fresh frozen	n/a	n/a
	90/90 intraosseous wiring augmented with cannulated screws						

The results of this study, originally recorded in [N], were converted to [Nm] by the formula $\vec{M} = \vec{F} \times \vec{a}$. The results of Ayres et al. recorded by the authors in kilogram-force [kgf] were converted to [N] by the factor 1 [kgf] $\equiv$ 9.806650 [N]. In case of missing parameters, "n/a" (not applicable) was inserted in the table field. Capo et al. only presented the absolute value for the intramedullary linked screw. Alluri et al. presented no absolute values but mentioned that there was no difference between the two techniques when tested to catastrophic failure.

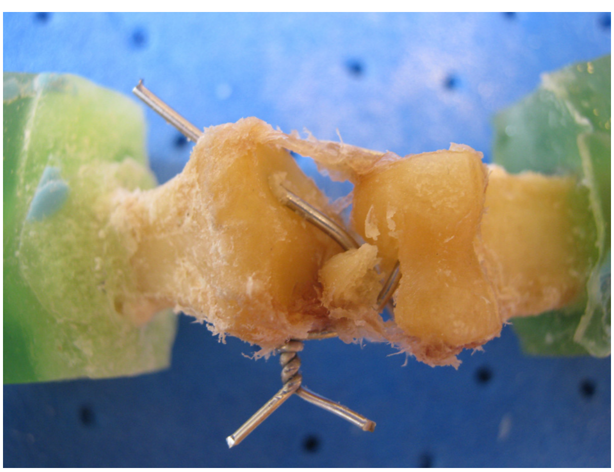

Fig. 6. Photograph of bony destruction after failure of intraosseous wiring specimen.

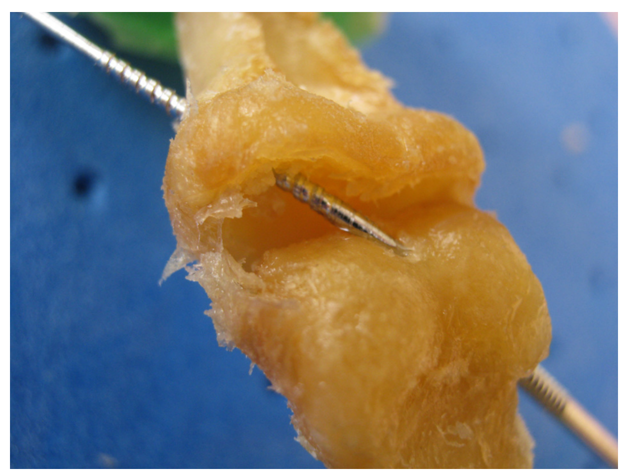

Fig. 7. Photograph of bony destruction after failure of compression wire specimen.

carrying larger weights or opening a jar, those activities should be avoided postoperatively in any case [16,18–20]. Nevertheless, high primary strength is surely advantageous in case of an abrupt trauma or incompliant patients [5,16].

Some might point out the chosen 20° fusion angle is too low, as the PIP joint might be fused in more flexion. We used 20° to ensure our findings would be comparable to the above-mentioned biomechanical studies that used a fusion angle between 20° and 30° [3,5,9,14,16,21].

Moreover the use of human cadaver bones for biomechanical testing along with the effect of their storage has been a controversial issue for some time. Though some authors point out the benefits of synthetic bone models as an alternative, cadaver bones are still considered to be the most realistic representation of in vivo mechanical properties. At the same time, many studies have shown a variable effect of alcohol fixation on certain mechanical properties, which may limit their use in biomechanical testing [22–25]. But since both techniques were tested on the same kind of specimen and those specimens were stored in formalin for the same amount of time, this should not be considered a disadvantage. Our sample size is comparable to those of other biomechanical studies on PIP joint arthrodesis, hence no power analysis was done because of the limited number of specimen available [3,15,16].

A third control group using a single K-wire was not included because the goal was to compare different usable in vivo techniques for PIP joint fusion. A single K-wire is not normally used in PIP joint fusion.

Further biomechanical studies should be done to evaluate the performance of compression wires compared to other established techniques such as tension band wiring or compression screws, which have performed favorably in other biomechanical trials [3,9,15]. In addition, consideration should be given to evaluating additional planes of motion, such as radial and ulnar bending, flexion bending and rotational stability as well as pressure measurements over the arthrodesis site [3,14,16,21].

5. Conclusion

Given the results of the biomechanical tests and their lack of comparability to studies by other authors using different techniques, there is no definitive answer to the question of whether the compression wire is suitable for PIP joint arthrodesis. But given that the results of the compression wire are within the range achieved by intraosseous wiring, it should be further evaluated in biomechanical and clinical trials.

Disclosure of interest

A.Z. Workshop instructor and lecturer for Königsee Implantate GmbH (Am Sand 4/OT Aschau, 07426, Allendorf, Germany).

The other authors declare that they have no competing interest.

Acknowledgements

We thank Mr. Axel Sckell, M.D., for the statistical analysis and Mrs. Alexandra Quooss for the biomechanical inputs.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version at: https://doi.org/10.1016/j.hansur.2019.07.002.

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