Foot and Ankle Surgery xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Foot and Ankle Surgery

journal homepage: www.elsevier.com/locate/fas

Evaluation of different shape-memory staple configurations against crossed screws for first metatarsophalangeal joint arthrodesis: A biomechanical study

H. Willmott[a,*], Z. Al-Wattar[a], C. Halewood[b], M. Dunning[a], A. Amis[b,c]

[a] Department of Orthopaedics, Conquest Hospital, East Sussex Hospitals NHS Trust, United Kingdom
[b] The Biomechanics Group, Department of Mechanical Engineering, Imperial College London, United Kingdom
[c] The Musculoskeletal Surgery Lab, Department of Surgery & Cancer, Imperial College London, United Kingdom

ARTICLE INFO

Article history:
Received 18 February 2017
Accepted 2 March 2017
Available online xxx

Keywords:
Arthrodesis
Metatarsophalangeal joint
Staples
Screws
Biomechanics

ABSTRACT

Background: The first metatarsophalangeal joint may be fused in order to treat arthritis or instability. The use of shape-memory staples for fixation is well recognised, but little work has been done into the optimal configuration of staples.

Methods: The structural behaviour of first metatarsophalangeal joint (MTPJ) arthrodeses using shape-memory staples or crossed screws was studied using cadaveric porcine joints. Five fixation configurations were tested: single vertical or horizontal staple, paired staples in dorsal-medial configuration (0–90° to the sagittal plane), paired staples in oblique orthogonal configuration (45–135°); or two crossed screws. Specimens were loaded in cyclical dorsiflexion for 1000 cycles. Plantar gapping and shearing were measured. Specimens were then loaded to failure.

Results: Cyclic testing caused more shear in the 45–135° staples than the crossed screws (1.0 mm ± 0.5 mm compared to 0.14 mm ± 0.4 mm, $p < 0.01$). No significant difference was found in plantar gap formation. Single vertical and horizontal single staples failed at 15N and 19.

Conclusions: N, respectively. Paired 0–90° staples failed at 43 N ± 9 N, significantly lower than the 45–135° staples (141 N ± 25 N; $p < 0.001$) and crossed screws (180 N ± 67 N; $p < 0.001$). There was no significant difference between the 45–135° staples and crossed screws. Screws failed by sudden cortical fracture; staples displayed gradual pull-out and shearing. First MTPJ arthrodeses fixed with single staples are not recommended. Arthrodeses fixed with staples at 0–90° to the sagittal plane were significantly less strong than two crossed screws. However, positioning oblique staples at 45–135° significantly improved stability, creating a construct as strong as, crossed screws. None of the constructs was strong enough for immediate weight bearing.

1. Introduction

The first metatarsophalangeal joint (MTPJ) may be affected by deformity, osteoarthritis and instability associated with rheumatoid arthritis and neuromuscular conditions such as cerebral palsy and polio. A reliable and widely used procedure for the treatment of these conditions is arthrodesis of the first MTPJ. Stable fixation of the arthrodesis is imperative for fusion to occur.

There are a number of described techniques to stabilise the arthrodesis, including wires, screws, plates and combinations thereof. There have been many clinical and biomechanical studies investigating the optimum configuration of these fixation methods [1–3]. More recently, a device known as a shape-memory staple has been developed. Shape-memory staples are made of equiatomic alloys: at low temperatures the staple is malleable; at body temperature the staple changes shape and the legs of the staple move towards each other (Fig. 1). These devices can be used to stabilise and provide compression across an arthrodesis [4,5]. A unique aspect of shape-memory staples is that they exert continuous compression when heated to body temperature, known as dynamic compression [6]. This contrasts with screws, which exert a fixed amount of compression that cannot be increased once the device is in situ. It has been postulated that movement at the arthrodesis may result in screws losing their hold, whereas staples would continue to provide compression [3].

The first reported use of shape-memory staples was in 2004 in a small clinical case series [7]. There have been two other

* Corresponding author at: Department of Orthopaedics, Conquest Hospital, The Ridge, St Leonards On Sea, East Sussex TN37 7RD, United Kingdom.
E-mail address: hwillmott@nhs.net (H. Willmott).

http://dx.doi.org/10.1016/j.fas.2017.03.001
1268-7731/

Fig. 1. Shape-memory staples as equiatomic alloys.

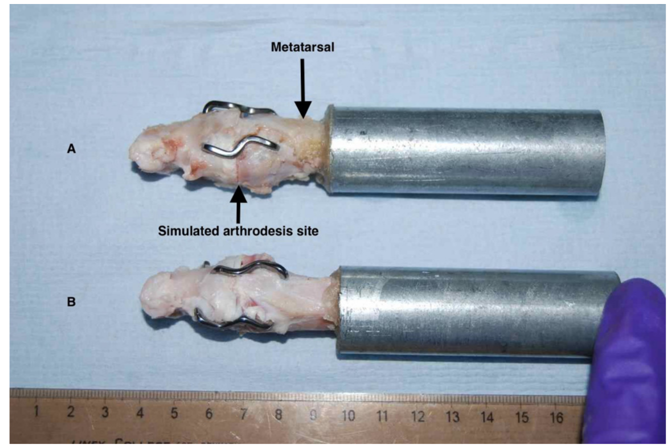

Fig. 2. Simulated arthrodesis. Proximal ends of the metatarsals mounted in tubes using PMMA cement: (A) Perpendicular 0–90 configuration (B) oblique 45–135 configuration.

retrospective case-series describing the technique [1,2]. All of these studies describe the use of two staples in an orthogonal configuration, with one staple positioned dorsally and the other directly medially (at 0° and 90° to the sagittal plane). No evidence has been presented to prove that this is the most stable configuration. Two biomechanical studies have previously been conducted using shape-memory staples. The first was a cadaveric study, which compared two oblique staples augmented with a K-wire to a plate and screw construct, with no variation of staple configuration examined [3]. The second used a Perspex-block model and compared the compression achieved by two different types of shape-memory staple [4]. No studies have compared different configurations of shape-memory staple.

1.1. Aims and hypotheses

This biomechanical in vitro study aimed to determine the optimum configuration and number of memory-staples needed to provide maximum stability to first MTPJ arthrodeses. It was hypothesised that:

1. Staples placed closer to the plantar surface will resist dorsiflexion moment more effectively and result in a stronger and more rigid construct than those held with dorsally-positioned staples.
2. Under cyclic loading, arthrodeses held with staples compared to screws will exhibit different biomechanical properties. When applying cyclic loading, staples will provide more stable construct due to their property of dynamic compression in comparison to screws that will exhibit loosening and progressive displacement over time.

2. Materials and methods

Porcine hindquarter MTPJs were used as a model for the human joint. Porcine metatarsals are similar in size to those of humans, and have similar biomechanical properties [8,9].

The joints were disarticulated and kept in metatarsal-phalanx pairs. The proximal ends of the metatarsals were mounted coaxially in 25 mm steel tubes using polymethylmethacrylate (PMMA) cement. The distal articular surface of the metatarsal was removed with a planar bone resection 25 mm from and parallel to the end of the steel tube to ensure that the location and orientation of the arthrodesis was consistent. The phalanges were prepared in a similar fashion, providing two flat surfaces to create the arthrodesis (Fig. 2). The arthrodesis was temporarily fixed with 1.6 mm K-wires. Each metatarsal-phalanx pair was then fixed using one of the following:

- A single vertical staple inserted from the dorsal aspect;
- A single horizontal staple;
- Paired staples in orthogonal dorsal-plantar and medial-lateral configuration (0 and 90° to sagittal plane);
- Paired staples in an oblique orthogonal dorso-medial to plantar-lateral and plantar-medial to dorso-lateral configuration (45–135° to sagittal plane);
- Two crossed 3.5 mm partially threaded self-tapping cancellous bone screws (DePuy Synthes, Warsaw, IN, USA) directed in an oblique retrograde direction from the mid-axial point of the phalanx to engage the opposite cortex of the metatarsal.

The staples were BioPro Memory Staples (BioPro Implants, Port Huron, MI, USA), manufactured from 2 mm diameter Nitinol® wire, a nickel–titanium alloy. The bridge width was 20 mm and leg length was also 20 mm. In the porcine metatarsal, this limb length just penetrated the opposite cortex, which is consistent with the manufacturer's recommendation. Staples were inserted according to the approved surgical technique, using a 2.4 mm diameter drill with a jig to create holes exactly 20 mm apart. Staples were stored at −20° C until immediately before implantation. After fixation the specimens were immersed in a water bath at 37° C for at least ten minutes in order to allow the specimen to reach equilibrium at body-temperature.

Specimens were tested using a single-axis screw-driven 5565 series Instron. This electromechanically load-testing device is widely used in biomechanical lab testing. It has an accuracy of ±0.5% for load measurement accuracy and strain measurement accuracy [16].

The testing device has a 5 kN (500 Kgf) load cell and Bluehill Version 2 software (Instron, High Wycombe, UK) along with a bespoke testing rig (Fig. 3). The load cell converts the load into an electrical signal that the control system measures and displays. The rig held the steel tube horizontally, plantar side facing upwards, allowing a ram attached to the load-cell on the moving crosshead of the Instron to be located on the condyles of the phalanx. This replicated the dorsiflexion moment experienced by post-operative weight bearing. The whole rig was positioned inside a water tank which was kept at 37 °C throughout testing (Fig. 3).

Please cite this article in press as: H. Willmott, et al., Evaluation of different shape-memory staple configurations against crossed screws for first metatarsophalangeal joint arthrodesis: A biomechanical study, Foot Ankle Surg (2017), http://dx.doi.org/10.1016/j.fas.2017.03.001