Stiffness Measurement of Elastic, Nitinol Plates for Fracture Fixation: Correlation to Finite Element Simulations before and after Shape Transformation

+[1]Olender, G D; [2]Pfeifer, R; [3]Müller, CW; [3]Gösling, T; [2]Barcikowski, S; [1]Hurschler, C
+[1]Laboratory for Biomechanics and Biomaterials, Department of Orthopaedics, Medical University of Hannover, Hannover, Germany
[2]Laserzentrum Hannover, Hannover, Germany
[3]Department of Orthopaedics, Medical University of Hannover, Hannover, Germany
christof.hurschler@ddh-gruppe.de

INTRODUCTION:

Nitinol is a promising biomaterial due to its remarkable shape changing characteristic, biocompatibility and hyperelasticity [1]. Until now, very limited applications have been tested for use of Nitinol plates in the area of fracture fixation. In this study, the bending stiffness of various dogbone shaped plates was tested by four-point bending before and after shape transformation. These transformations were then modelled by the finite element method (FEM). Results show that the stiffness of a fracture fixation plate can be altered in a consistent manner and that FEM models were useful for stiffness prediction. These FEM models also provided a more convenient way to estimate shape altered stiffness that could not be directly determined by other calculations, *i.e.* the area moment of inertia.

The concept of modulating implant stiffness for fracture repair has been suggested as a means to stimulate bone formation and accelerate healing time [2]. Early designs of wire implants have been tested *in-vivo* without immunological or histological disturbances in a rat model after the implant changed shape through induction heating [3]. Manipulating when implant stiffness can be altered and how great a percent change it will transform based on specific design configuration, can be beneficial to osteosynthesis as well as avoiding additional invasive procedures [3].

METHODS:

The sample-plates tested were created by laser welding together individual Nitinol plates [4]. The parameter changed between the groups investigated was plate thickness (2.5, 3.0, 3.5 and 4.0 mm), each group consisted of 3 samples. The plates were tested according to the protocol described in ISO 9585: 1990(E), providing a standardized formula for equivalent stiffness. A four-point bending rig was attached to the uniaxial MTS test machine (Mini Bionix 858, MTS Systems, Minneapolis, USA). The testing rig was surrounded by a Plexiglass chamber that held water, which was cycled by a thermostat/pumping device (CC-205, Huber, Offenburg, Germany). The heating chamber of the device controlled the temperature, as it was raised from 37º C, for testing, to 55º C, initiating the shape change. The plates were allowed to cool, back to 37º C and were tested again. CAD models were designed with Solid Edge and investigated using FEM in NX 7, (Siemens PLM Software GmbH, Köln).

RESULTS:

Four-point bending of a single Nitinol plate changed equivalent stiffness from 0.77 Nm^2 to 3.07 Nm^2 due to a combined effect of material phase and shape change. This was an increase of 301%. When the sample was cooled and tested again at 37º C, the increase in stiffness was 160% over the dogbone shape baseline. The transition of phase (Austenite – Martensite) thus increased stiffness by 54% (**Fig. 1**).

The repeated bending tests between the pre transformation (dogbone) and post transformation (straight) all showed significant increase in stiffness ($p<0.05$) by one sided, paired Student T-tests (**Fig. 2**). The plate of 4 mm thickness had the highest stiffness for the dogbone samples (0.99 Nm^2; SD 0.03) and for the straight shape (1.45 Nm^2; SD 0.06).

FEM results also displayed an increase in stiffness between the two shape forms of the same thickness dimension. The percent differences were similar to the experimental results, although the agreement varied (**Fig. 2, Table 1**). The greatest change in area moment of inertia was calculated at 2.34 mm^4 for the dogbone configuration and for 13.68 mm^4 for the straight configuration in the 3.5 mm plate.

DISCUSSION:

Calculation of the area moment of inertia alone is not sufficient to predict stiffness changes because the changes in cross section affect only a relatively small central section, and are not homogeneously throughout the plate. However, FEM predictions showed a much better relationship to correlate to experimental results.

In this study, we found that there were significant changes in bending stiffness due to a temperature induced configuration change. Amongst the various design thicknesses were varying degrees of stiffness alteration after transformation. The shape transformation within the sample groups also displayed consistency (low SD) as seen in (**Fig. 2**).

Therefore, it would be possible to test these implants which can change shape, in future animal experiments to measure the impact of altered implant stiffness has on the fracture healing process.

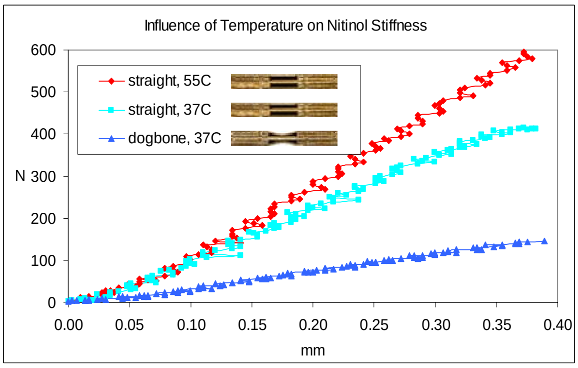

Figure 1: *Tests for a single Nitinol plate, 3 mm, were conducted at 37º C, 55º C and again after cooling back to 37º C.*

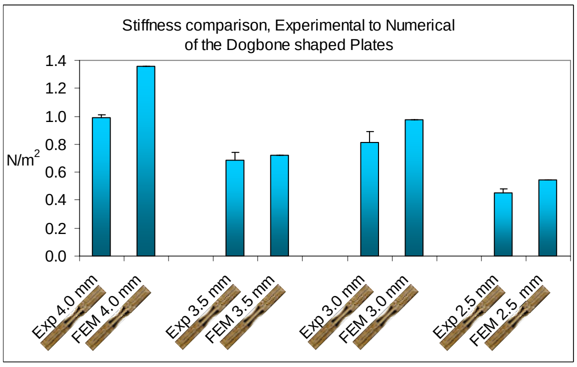

Figure 2: *Stiffnesses of the plate before transformation (dogbone) comparing experimental and finite element results.*

Table 1*: Percent difference comparisons of stiffness after a transformation from baseline shape (dogbone). Shown are experimental results, FEM predictions, and area moment of inertia (AMI) changes.*

Test method	Thickness	Percent diff
Experimental	2.5 mm	40%
FEM	2.5 mm	35%
AMI	2.5 mm	164%
Experimental	3.0 mm	24%
FEM	3.0 mm	26%
AMI	3.0 mm	102%
Experimental	3.5 mm	73%
FEM	3.5 mm	149%
AMI	3.5 mm	483%
Experimental	4.0 mm	47%
FEM	4.0 mm	91%
AMI	4.0 mm	283%

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