The mechanical testing of a novel interlocking forearm nail

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Abstract

Background

Mechanical testing of newly designed implants provides valuable insight into their mechanical properties. This provides surgeons with information about implant choice for the treatment of fractures and the effect of the implant’s mechanical properties on fracture healing.

Methods

A novel interlocking forearm nail was subjected to standardised mechanical testing according to the Standard Specification and Test Methods for Intramedullary Fixation Devices (ASTM 1264-16), using static and dynamic four-point bending and static torsion (ASTM STP 588). Three nails were used for the static bending and torsion and nine for the dynamic bending tests. All nails were catalogued, numbered and photographed before testing.

Results

The mechanical testing results showed a mean force yield (Fy) of 566 ± 20 N, a moment of yield (My) 10.75 ± 0.37 Nm, a stiffness of 67.10 ± 2 N/mm and structural stiffness of 1.53 ± 0.50 m². The torsional stiffness of the nail was 0.088 ± 0.002 Nm/°. The four-point dynamic bending test showed a fatigue strength of 5.23 Nm. This value was determined using the semi-log moment/number of cycles (M-N) diagram and showed a 50% failure at a million cycles. If the moment were reduced to 4.4 Nm, mathematically, the survival rate would improve to 90%.

Conclusion

The results from this mechanical testing show that this novel intramedullary forearm nail can resist mechanical forces experienced during fracture healing and could potentially be used in future clinical studies.

Level of evidence: Level 4

Keywords: mechanical testing, ASTM, load, yield, stiffness, fatigue strength

Introduction

The mechanical properties of implants are one of many factors that contribute to the mechanobiological environment for fracture healing. Mechanical testing of newly designed implants provides valuable insight into their mechanical properties. This provides surgeons with information about implant choice and the effect of the implant’s mechanical properties on fracture healing.1

Although not weight-bearing, radius and ulna fracture fixation are still exposed to significant in vivo forces, including pronation/supination rotational and bending moments created when carrying objects. The ability of an implant to withstand these forces is considered when these devices undergo mechanical testing prior to clinical use.

Compression plate fixation of the forearm provides absolute stability with no fragment movement while bridge plating and nail fixation will provide relative stability with some movement between fragments. Restoration of length and alignment and the ability to control rotation make intramedullary nail fixation ideal for managing long bone fractures. Comminuted and segmental fractures, which are frequently seen in high-energy gunshot wounds, are particularly well suited to intramedullary fixation as the intramedullary nail provides load-sharing mechanics, restores anatomy and fragment stability and has a minimal invasive insertional approach which can be important when soft tissue injuries are involved. With nail fixation of simple forearm fractures, the bone provides some mechanical support, but with comminuted or segmental fractures,
the nail provides most of the support, so any implant must have the mechanical properties to maintain stability until fracture union.

A novel interlocking forearm nail was designed to address both length and rotational stability in forearm fractures. The implant design was based on findings from a computed tomography scan anatomical study. In the design process, the biomechanical properties of bone, the modulus of elasticity of metals and the mechanical testing process of similar products in the literature were used to inform the process.

The modulus of elasticity of bone ranges from 10–28 GPa (gigapascals or kN/mm²), and for the radius specifically 10–17 GPa. Titanium specifically has a modulus closest to bone and better fatigue than stainless steel; after taking this into account, titanium (Ti6Al4V ISO 5832-3) was utilised.

The nail is machined to the correct specifications instead of being cast or 3D printed. The base material, a solid tube, is made by additive manufacturing (AM), an advanced manufacturing technology using 3D CAD by adding materials in a layer-by-layer fashion that allows products with geometric complexities as simple as solid tube structures or complex shapes like replacement mandible bones to be made.

This study reports the results of standardised mechanical testing of a novel forearm nail to ascertain whether the implant would withstand physiological load during fracture healing.

**Methods**

Standardised mechanical testing to ascertain the clinical applicability of the new nail design was conducted. Implants are generally exposed to between 150 000 and 200 000 cycles of repeated strain over three months until fracture union. To simulate the upper limit of expected cycles until union, fatigue testing is performed at a standard amount of one million cycles. The four-point bending with static and dynamic tests and static torsion tests are the implants’ prescribed tests. Saka et al. showed a mean bending test force of 539.75 N and a mean torsional force of 0.028 Nm°. Gardner et al. used 250 N force represented by partial yield force, moment of yield, stiffness and structural stiffness. The results are reported as yield force, moment of yield, stiffness and structural stiffness.

Dynamic testing was performed in a WPN Servo-hydraulic test rig (MTS 858 Mini Bionix) with a 38 mm centre span, and the distance to the loading points was also 38 mm (Figures 1 and 2). A constant force at a rate of 0.1 mm/s was applied until failure. In this test, failure was defined as permanent deformation, breakage or buckling. The test was stopped, and the maximum force was measured in Newtons (N) (Figure 3). The results are reported to industry standards (ASTM STP 588). All nails were catalogued, numbered and photographed before testing. Three nails were used for the static bending and torsion, and nine nails were used for the dynamic bending tests. The test device specifications are shown in Table I.

The nails for four-point bending were placed on the hydraulic rig (MTS 858 Mini Bionix) with a 38 mm centre span, and the distance to the loading points was also 38 mm (Figures 1 and 2). A constant force at a rate of 0.1 mm/s was applied until failure. In this test, failure was defined as permanent deformation, breakage or buckling. The test was stopped, and the maximum force was measured in Newtons (N) (Figure 3). The results are reported as yield force, moment of yield, stiffness and structural stiffness.

Dynamic testing was performed in a WPN Servo-hydraulic test rig and followed a sinusoidal cyclic load waveform at a frequency of 5 Hz and programmed for 1 million cycles or until failure. The results were plotted on a moment/number of cycles (M-N diagram) graph to determine the fatigue strength that 50% of the specimens will survive at one million cycles.

![Figure 1. Illustration showing the distance between four points for the four-point bending test](image)

![Figure 2. Nail placed in the four-point testing rig](image)

**Table I: Testing device specifications**

<table>
<thead>
<tr>
<th>Test device</th>
<th>IMA identification no.</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTS 858 Mini Bionix</td>
<td>PMK-No A4_2</td>
<td>Static tests</td>
</tr>
<tr>
<td>WPN Servo-hydraulic test rig</td>
<td>PMK-No A4_7</td>
<td>Bending fatigue</td>
</tr>
<tr>
<td>Calliper (300 mm)</td>
<td>MNK-NO A4-L16</td>
<td>Distance measurement</td>
</tr>
<tr>
<td>Angle gauge</td>
<td>MNK-NO A4-W-4</td>
<td>Angle measurement</td>
</tr>
</tbody>
</table>
The test setup for the dynamic torsional test has the nail clamped between a base plate and hydraulic rotation device (Figure 4). The system rotates at a fixed rate of 5° per minute until failure. The results are reported as torsional stiffness.

**Results**

Following the ATSM 1264-16 guidelines, a report was supplied showing photos of the setup, the results and photographs of breakages. A summary of the testing parameters is shown in Table II. The mechanical testing results showed a mean force yield (Fy) of 566 ± 20 N, a moment of yield (My) 10.75 ± 0.37 Nm, a stiffness of 67.10 ± 2 N/mm and structural stiffness of 1.53 ± 0.50 m² (Table III). The torsional stiffness of the nail was similar in the three specimens, with a mean result of 0.088 ± 0.002 Nm/° (Table IV). The four-point dynamic bending test showed a fatigue strength of 5.23 Nm. This value was determined using the semi-log M-N diagram and showed a 50% failure at one million cycles.

Due to the large numbers used for the cycles and the small numbers used for the moment, the graphs are presented as cycles in a logarithmic scale on the X-axis and the moment in a linear scale on the Y-axis. If the moment was reduced to 4.4 Nm, mathematically, the survival rate improved to 90% (Figure 5). The force applied can be calculated mathematically with the forearm as the lever arm: moment [Nm] = force [N] × lever arm [m]. If the forearm from elbow to palm measures 0.2 m, the force would be 22 N or 2.2 KgF (Kilogram-force).

All the samples used for dynamic testing were tested until failure, and the place of failure was then noted. To this end, photos of

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**Table II: Summarised testing parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ASTM F1264-16 A1</th>
<th>ASTM F1264-16 A2</th>
<th>ASTM F1264-16 A3</th>
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<tbody>
<tr>
<td><strong>Test type</strong></td>
<td>Four-point bending (static)</td>
<td>Static torsion</td>
<td>Four-point bending (dynamic)</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td>Displacement controlled</td>
<td>Angle-controlled</td>
<td>Sinusoidal cyclic load waveform</td>
</tr>
<tr>
<td><strong>Number of specimens</strong></td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td><strong>Rate/frequency</strong></td>
<td>0.1 mm/s</td>
<td>5°/min</td>
<td>5 Hz</td>
</tr>
<tr>
<td>$y^2=sl(1+2c)/(1500)$</td>
<td>1.07 mm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Ratio (Mmin/Mmax)</strong></td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Number of cycles (run out)</strong></td>
<td>-</td>
<td>-</td>
<td>1 000 000</td>
</tr>
</tbody>
</table>

**Results**

<table>
<thead>
<tr>
<th></th>
<th>Yield force</th>
<th>Moment at yield</th>
<th>Stiffness</th>
<th>Structural stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test environment</strong></td>
<td>Ambient condition</td>
<td>Ambient condition</td>
<td>Ambient condition</td>
<td></td>
</tr>
</tbody>
</table>

**Table III: Results for static bending**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield force Fy (N)</th>
<th>Moment at yield My (Nm)</th>
<th>Stiffness Fy (N/mm)</th>
<th>Structural stiffness EI (Nm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F022/20-1</td>
<td>559</td>
<td>10.62</td>
<td>67.4</td>
<td>1.54</td>
</tr>
<tr>
<td>F022/20-2</td>
<td>550</td>
<td>10.45</td>
<td>64.9</td>
<td>1.48</td>
</tr>
<tr>
<td>F022/20-3</td>
<td>588</td>
<td>11.17</td>
<td>69.0</td>
<td>1.58</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>566</td>
<td><strong>10.75</strong></td>
<td><strong>67.1</strong></td>
<td><strong>1.53</strong></td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>20</td>
<td>0.37</td>
<td>2.0</td>
<td>0.05</td>
</tr>
</tbody>
</table>
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the broken nails were supplied to show where each nail failed (Figure 6). In this example, the nails broke in the shaft and not through the locking holes.

**Discussion**

Mechanical testing of newly designed implants provides valuable insight into their mechanical properties and ability to withstand expected physiological forces during fracture healing. This provides surgeons with information about implant choice for fractures and the effect of the implant’s mechanical properties on bone and fracture healing.

Bone is anisotropic, indicating different tolerances to forces applied from different directions. Normal bone can withstand axial forces of approximately 15 000 N and tangential forces of 6 000 N.\(^5\) The human upper limb seldom generates forces exceeding 200 N.\(^12,13\) Hallaj et al. and Putnam et al., in various tests of the wrist function for jar twist and grip, showed that the maximum force generated was 47–65 N.\(^14,15\) Hori used 140 N when testing wrist strength and transfer of mechanical loads to the carpus.\(^16\) Peine et al. tested dorsal plates for distal radius fractures and applied a maximum force of 400 N for testing plate strength.\(^17\) Implants are expected to withstand up to 200 N forces to allow fracture healing.

The human forearm is rarely exposed to forces exceeding 200 N, but any implant is expected to survive this threshold tolerance. In an article by Saka et al., the yield strength of the radial nail had a mean of 539 N and torsional strength of 0.028 Nm/°.\(^3\) The yield strength in the current study was 566 N and a higher torsional strength of 0.080 Nm/°. As this is a locked nail, the amount of comminution of the fracture affects how much of the torsional forces are transferred to the prosthesis. With load-sharing nails, the length of cortical contact is reduced in severely comminuted fractures and a higher torque resistance is therefore beneficial.\(^18\) This shows the proposed implant to have results equivalent to contemporary forearm nails in clinical use.

Dynamic testing showed a moment strength of 5.2 Nm is 50% survival with one million cycles. With extrapolation from the graph to 4.4 Nm, the survival of the implant improves to 90%. This is equivalent to exposing the nail to a 2.2 kg weight held in the hand. As the lever arm or forearm, in this case, gets longer, the force will reduce. This will allow the clinician to allow mobilisation of the forearm while allowing functional activities with a weight limit until union of the fracture.

The standardised testing of implants by independent companies provides integrity for the results. These standard tests limit the number of implants needed for testing that may result in slightly different results and could help make the semi-logarithmic graphs more accurate.

**Conclusion**

The results from the study’s mechanical testing show that this novel intramedullary forearm nail can resist mechanical forces experienced during fracture healing and could potentially be used in future clinical studies.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Torsional stiffness (Nm/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F022/20-1</td>
<td>0.088</td>
</tr>
<tr>
<td>F022/20-2</td>
<td>0.090</td>
</tr>
<tr>
<td>F022/20-3</td>
<td>0.086</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>0.088</strong></td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td><strong>0.002</strong></td>
</tr>
</tbody>
</table>

Figure 5. Semi-logarithmic graph illustrating the survival probability points for the nail.

Figure 6. The nails after failure, to see the exact position of the break.

Table IV: Results for torsional stiffness.
Ethics statement
The authors declare that this submission is in accordance with the principles laid down by the Responsible Research Publication Position Statements as developed at the 2nd World Conference on Research Integrity in Singapore, 2010. Prior to commencement of the study, ethical approval was obtained from the following ethical review board: Stellenbosch University Health Research Ethics committee, S20/04/100 (PhD).

Declaration
The authors declare authorship of this article and that they have followed sound scientific research practice. This research is original and does not transgress plagiarism policies.

Author contributions
HSP: study conceptualisation, first draft preparation, data analysis and manuscript revision
MCB: data analysis and manuscript revision
NF: data analysis and manuscript revision

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References