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The effect of load obliquity on the strength of locking and nonlocking constructs in synthetic osteoporotic bone

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ABSTRACT

The biomechanical performance of internal fracture fixation depends on several factors. One measure of performance is the strength of the construct. The objective of this biomechanical study was to identify the effect of load obliquity on the strength of locking and nonlocking plate and screw constructs. For this study, plates and screws were fixed to synthetic osteoporotic bone that had a 1 mm thick synthetic cortical shell. An 8-hole, 3.5 mm thick hybrid plate was fixed with either two 3.5 mm major diameter locking screws or two 4.0 mm major diameter cancellous screws. Forces were applied at 0, 45, and 90 degrees to the plate normal. Eight specimens were loaded to failure for each group. When loads were applied normal to the plate, the nonlocking construct failed initially at higher loads (123.2 ± 13.2 N) than the locking construct (108.7 ± 7.6 N, $P = 0.020$). For oblique loads, the locking construct failed at higher mean loads but the difference of means was not statistically significant (167.7 ± 14.9 N compared to 154.2 ± 9.4 N, $P = 0.052$). For loads parallel to the plate, the locking construct was much stronger than the nonlocking construct (1591 ± 227 N compared to 913 ± 237 N, $P < 0.001$). Stiffness and Energy outcomes are also compared.

1. Introduction

In the last decade, locking plate technology has proliferated. Several biomechanical studies have demonstrated improved stability with the use of locking plates [1–8]. One feature of a locked plate construct is the fixed angle between the screw and plate, which can provide a biomechanical advantage in some clinical scenarios. However, other studies have found the conventional constructs to be superior in osteoporotic bone and bone surrogate [9–14]. In aggregate, these studies show that the performance of fracture plating also depends on geometric and loading factors. The loads carried by fracture plates cause at least two distinct failure mechanisms at the screws: cut out and axial pullout. Stripping, as a mechanism of failure, is defined as localized shear failure of bone at its interface with the screw and is the primary failure mechanism during screw pullout and thus construct failure. Alternatively, a locking screw may cut out of the bone because under oblique or shear loads the screw is unable to pull out of the bone. A mixed mechanism of failure is also possible. The outer diameter and length of the screw define the surface of a cylinder along which the stripped bone shears [15]. Therefore, the major diameter of the screw has the largest effect on pullout strength, more so than minor diameter and pitch [16–23].

All of these factors are complex and poorly understood in the context of clinical orthopedics and decision making. Relatively little has been published examining the difference between locking and nonlocking screw constructs where the ranges of loading directions are compared using consistent methods. This gap in the literature has important clinical implications to the surgeon when deciding whether to use nonlocking or locking screws. The objective of this study is to differentiate the strength of locking and nonlocking plate and screw constructs subjected to normal, oblique, and parallel loads in synthetic osteoporotic bone.

2. Materials and methods

2.1. Specimens and preparation

Synthetic bone was used to mimic osteoporotic bone (Sawbones, Pacific Research Laboratories, Vashon Island, WA, USA). The bone consisted of commercially available closed cell polyurethane foam with a density of 0.08 g/cm^3 (5 pcf – Sawbones part #1522-23) representing cancellous bone, bonded to a 1 mm short fiber filled epoxy sheet to represent the cortex (Sawbones part #3401-1). The synthetic bone was processed into 40 mm by 40 mm by 60 mm specimens. An

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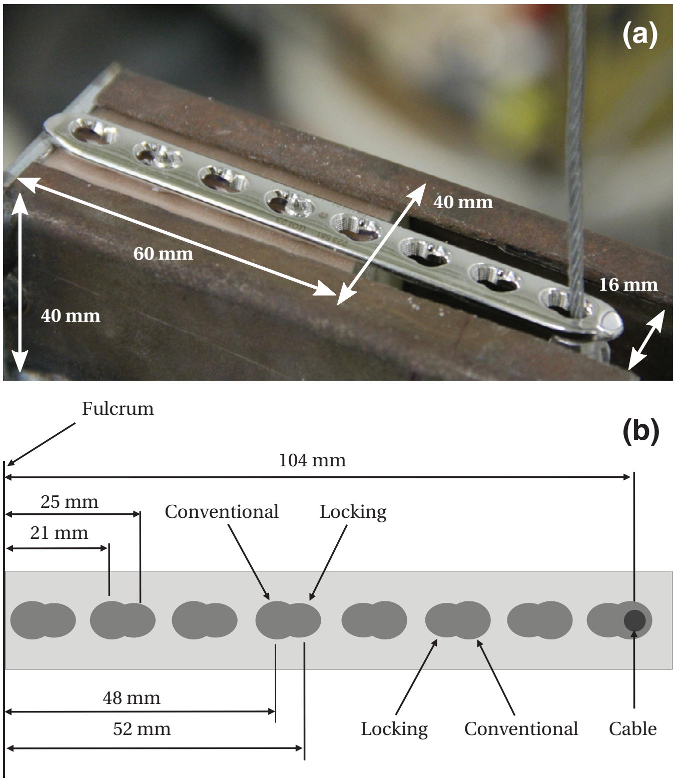

Fig. 1. (A) Fixture including bone surrogate, plate, and two locking screws. (B) Screw locations relative to the fulcrum.

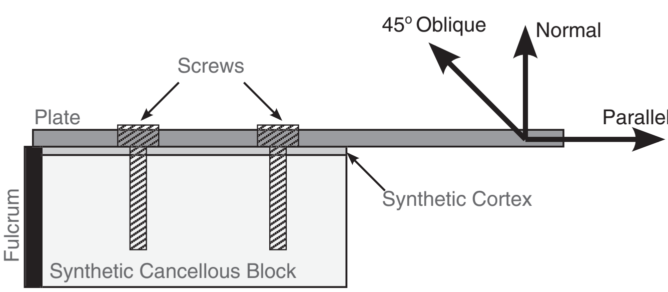

Fig. 2. Angular range of loads applied to the constructs.

8-hole, 3.5 mm thick hybrid (locking or compression) plate (Synthes, West Chester, Pennsylvania, USA, part #223.581) was affixed with either two self-tapping 3.5 mm major diameter, fully threaded locking screws (Synthes, part #212.12) placed in the locking holes of the plate or two self-tapping 4.0 mm major diameter fully threaded cancellous screws (Synthes, part #206.032) placed in the nonlocking holes of the plate, all screws being 32 mm in length (Fig. 1). Thus, two screw-plate interface types were investigated representing locking and nonlocking plate fixation in synthetic osteoporotic bone. Forces were applied at 0, 45, and 90 degree angles to the plate normal direction (i.e., normal, oblique, and parallel loads to the plate, respectively) (Fig. 2). The angles span the range of physiological loads and provide data useful for interpreting the strength of the constructs in many clinical scenarios. The line of action for normal and oblique forces was through the last hole of the plate, four holes from the nearest screw. Thus, the plate construct carried a bending moment and an oblique force consistent with most physiological loading mechanisms. The parallel loads were applied through direct grasping of the plate, and thus, the line of action was approximately through the plate centroid.

2.2. Loading and testing

The specimens were attached via a fixture to the base of a Bionix servo-hydraulic testing frame (MTS Systems Corp, Eden Prairie, MN, USA) (Fig. 3). Normal and oblique forces were applied to the plate by way of a 2.4 mm diameter steel cable through the eighth hole in the plate. A 500 N load cell was placed in-line with the line of action of the cable and used to measure the applied load. Parallel loads were measured using the 25 kN load cell attached to the load frame. The load frame crosshead was advanced at 5 mm/min to a displacement of 50 mm. This is consistent with previous published studies [24–26]. Time (s), crosshead displacement (mm), and load (N) were sampled at a rate of 128 Hz. The point at which the load–displacement curve first dropped, not the ultimate maximum peak, was assumed to represent initial failure (i.e., strength) of the construct. New plates, screws, and synthetic bone were used for each test.

A power analysis, which was based on a series of preliminary tests, estimated that eight specimens would be sufficient per group to achieve a power of 80% and a significance level of 5%. Thus, eight specimens were tested for each construct at each load angle.

2.3. Statistical analysis

A Shapiro–Wilk test was utilized to assess the normality of the acquired data. Analysis of Variance (ANOVA) was used to explore relationships between groups. All statistical analyses were performed using R version 3.0.1 (R Foundation for Statistical Computing, Vienna, Austria) at a significance level of 0.05.

3. Results

Experimental outcomes are reported in Figs. 4–6. To ease interpretation and to account for specimen and cable settling, the measured displacements were offset within each subgroup such that the linear portion of the curve passes through the origin (i.e., after specimen and cable settling and before initial failure).

For forces applied normal to the plate, the nonlocking construct failed at statistically higher loads (123.2 ± 13.2 N) than the locking construct (108.7 ± 7.6 N, $P = 0.021$, Fig. 4). For oblique loads, the difference in means was not statistically significant (154.2 ± 9.4 N nonlocking vs. 167.7 ± 14.7 N locking, $P = 0.052$, Fig. 5). For loads parallel to the plate, the locking construct failed at a higher mean load (1591.0 ± 227.0 N) than the nonlocking construct (913.7 ± 237.1 N, $P < 0.001$, Fig. 6). Parallel failure loads were also noted to have a higher relative variability than oblique and normal failure loads.

The locking construct was significantly stiffer against parallel loads than was the nonlocking construct (893.2 ± 157.0 vs. 349.8 ± 59.0 N/mm, $P < 0.001$). This was observed to be due to the rapid onset of "toggle" in the nonlocking screws. However, the difference in overall energy required to initiate failure did not achieve statistical significance (1793 ± 808 mJ locking vs. 1918 ± 518 mJ nonlocking, $P = 0.719$). This is because the more compliant nonlocking specimens experienced somewhat larger displacements prior to the initial failure at lower loads. The differences in stiffness against normal loads (12.2 ± 0.8 N/mm locking vs. 13.7 ± 1.2 N/mm nonlocking, $P = 0.013$) and oblique loads (20.1 ± 0.9 N/mm nonlocking vs. 23.9 ± 1.5 N/mm locking, $P < 0.001$) is not likely to be clinically relevant and the difference in energy to failure for normal (591 ± 81 mJ locking vs. 667 ± 78 mJ nonlocking, $P = 0.077$) and oblique (777 ± 120 mJ locking vs. 777 ± 68 mJ nonlocking, $P = 0.987$) is not statistically significant.

As the nonlocking constructs began to fail due to the normal and oblique load mechanisms, the screws were observed to pull out as their heads toggled in the plate. This effect can be seen as the first drop in the load-displacement curves. Similarly, the locking screws in the normal and oblique mechanisms had an initial drop in load that