Axial and shear pullout forces of composite, porcine and human metatarsal and cuboid bones

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Introduction

Fresh frozen human bone specimens are considered as golden standard for biomechanical testing, reflecting most appropriately the in vivo situation. However, they have several disadvantages such as ethical concerns, difficult and complicated acquisition, preparation, storage and handling which have to follow certain laboratory requirements [1]. The interindividual variance in mechanical properties and bone geometry of human samples directly influences biomechanical study results [2], sometimes hiding existing differences in-between bone-implant constructs.

Bone quality is reduced or even osteoporotic in most of the human bone specimens, especially the female ones, since donor age is almost always advanced. A valid alternative such as synthetic surrogate or animal bones is of high interest. Bones from several animals, especially porcine, bovine and ovine bones, have been used as human substitutes in biomechanical testing [3–8]. Because fixation techniques for young human nonosteoporotic bone could not be investigated in specimens with osteoporotic bone quality without influencing the results [3], porcine and bovine bones are often used as substitute for biomechanical studies on sports medical topics [3,5,6,8] and was partially investigated, and it could be shown that screw pullout and screw shear forces of porcine bone are close to nonosteoporotic human bone.

Materials and methods

Six surrogate large left first metatarsal fourth generation composite bones, made from specially formulated polyurethane foam and designed for biomechanical testing (Sawbones Europe, Malmö, Sweden, reference number C6278), six porcine cuboids (mean donor age 8 month, acquired from local slaughter), six human first metatarsals and cuboids of nonosteoporotic bone quality (mean donor age 32 years range, 12; 5 male, 1 female; 1 right, 5 left) and six human cuboids of osteoporotic bone quality (mean donor age 81 years range, 6; 4 male, 2 female; 4 right, 2 left) were used in this study, divided into five study groups with six specimens each. The intact cuboids, harvested from human and porcine feet, were scanned with a peripheral quantitative computed tomography scanner (Xtreme-CT, Scanco Medical AG, Brüttschellen, Switzerland) with a slice thickness of 123 μm and 854 evaluated slices per specimen for (BMD) evaluation before instrumentation.

A 3.5-mm, self-tapping stainless steel cortex screw (DePuy Synthes GmbH, Zuchwil, Switzerland), was inserted bicortically into each specimen after predrilling with a 2.5 mm drill bit. Axial pullout tests were performed after the instrumentation on a material testing machine (Instron 4302, Instron Inc., Canton MA, USA) with a 10 kN load cell, operated in displacement control mode at a cross-head speed of 5 mm/min. The screw head was inserted unlocked in the upper part of a testing jig, which was attached to the load cell. The midpoint of the screw head was aligned in the machine axis to ensure pure axial pullout force during the test. The bone specimens were fixed in the lower part of the jig, rigidly connected to the test frame, but restricting the specimen movement solely in the direction of the applied load (Figure 1A and B). Further, same instrumentation procedure, followed by pullout test, was repeated with 2.7 mm self-tapping stainless steel head locking (HL) screws (DePuy Synthes GmbH, Zuchwil, Switzerland) with...
predrilled Ø2.0 mm hole, inserted into each one of the specimens.

For shear load tests, the porcine and human cuboids were instrumented with bicortically placed 3.5 mm non-locking (NL) screws previously inserted in a NL plate hole to mimic the loading pattern of a NL screw in combination with a NL plate, where tilting of the screw in the plate hole during loosening in the bony screw hole is possible. Additionally, 2.7 mm HL screws were locked in the test fixture to mimic the loading pattern of a locking screw with locked screw head in the plate, according to the principle of internal fixator, where no tilting of the screw in the plate hole during loosening in the bony screw hole is possible. Predrilling was performed in the same manner as for pullout tests. Bones were embedded in a polymethylmethacrylate block. Screw tips were covered with plasticine before embedding to allow free movement of the screw in the bone during the test. The polymethylmethacrylate block was rigidly connected to the base plate of the test frame to fix the bone with the screw shaft axis oriented in the horizontal plane, orthogonal to the load axis of the testing machine. The plate was rigidly connected to a linear slide via a vise. The plate was moved orthogonally to the screw shaft axis to apply shear load to the screw. The screw head of the locking screw was fixed in a vise being rigidly connected to a linear slide to simulate HL. The vise was moved orthogonally to the screw shaft axis to apply shear load to the screw. Both, nonlocking and locking screws were loaded orthogonal to their shaft axis. Testing machine and load protocol for shear load tests were identical to the axial pullout tests (Figure 1C). Test setup for pullout and shear tests was similar to that described by Seebeck et al. [11].

Axial load and axial displacement were recorded from the test system’s transducers at a frequency of 10 Hz. Axial pullout stiffness and shear stiffness were determined from the linear part of the load–displacement curves, below the yield point. The ultimate axial pullout force and ultimate shear force was derived from the maximum value of the corresponding load–displacement curve, corresponding to Seebeck et al. [11].

Statistical analysis was performed using SPSS (IBM SPSS Statistics 19.0, SPSS Inc., Chicago, IL). The significance level was set to 0.05. Normal distribution within each group was evaluated by the Shapiro–Wilk Test. For the detection of significant differences between the groups, the one way analysis of variance and the unpaired t test and the Kruskal–Wallis test were used, both with Bonferroni post hoc correction. Correlation was analysed with Spearman’s correlation test.

Results

Mean stiffness under axial pullout force and mean ultimate axial pullout force values are provided in Table 1. Load–displacement curves of axial pullout testing of one representative specimen per group are shown in Figures 2 and 3. Osteoporotic human cuboid bone specimens exhibited the lowest stiffness values, whereas in composite bone specimens, the highest stiffness values were observed. The p-values of the respective comparisons are listed in Table 2 for 2.7 mm locking screws and in Table 3 for 3.5 mm NL screws. Porcine and nonosteoporotic human cuboids exhibited a comparable mean ultimate axial pullout force. Stiffness values were significantly higher for composite first metatarsal bones within both screw types compared to all other groups. Stiffness values were significantly lower for osteoporotic human cuboids within both screw types compared to all other groups except for nonosteoporotic cuboids using 2.7 mm locking screws.

Mean ultimate shear pullout force and mean shear stiffness of locked and nonlocked screws are summarized in Table 4. Load–displacement curves of shear testing of one representative specimen per group are shown in Figures 4 and 5. Porcine bone exhibited a mean ultimate shear force comparable to nonosteoporotic human bone.
Locking screws exhibited a significantly higher shear stiffness in all groups (all $p < 0.01$) than nonlocking screws.

Porcine bone specimens provided a significantly higher mean apparent BMD (325 mgHA/ccm $\pm 42$) than osteoporotic (159 mgHA/ccm $\pm 56$; $p < 0.01$) and nonosteoporotic (229 mgHA/ccm $\pm 25$; $p < 0.01$) human bone specimens. Comparing the apparent BMD of osteoporotic and nonosteoporotic human cuboid bones, the difference was not statistically significant. The apparent BMD and the axial pullout load of 3.5 mm cortical screws showed a rank correlation with a Spearman’s correlation coefficient of $r_s = -0.829$ for porcine bone and $r_s = 0.886$ for osteoporotic human bone.

**Discussion**

This study compared mechanical properties of porcine and synthetic composite foot bone to nonosteoporotic and osteoporotic human foot bone to evaluate the suitability of these substitutes for biomechanical studies.

Porcine bone exhibited a mechanical strength in axial pullout direction as well as in shear direction comparable to nonosteoporotic human bone. Porcine bone represents an adequate substitute for young human nonosteoporotic bone, which is difficult to acquire. Unlike humans, pigs have a plexiform bone with osteonal banding. On the other hand, the annual skeletal remodeling rate is similar to that in humans (20–50%). Size and shape of the porcine skeleton might restrict the use for human implant testing, especially with regard to long bones. Porcine and bovine bones are frequently used in biomechanical studies on cruciate ligament reconstruction [6,9], anchor fixation [5,10] and acromioclavicular ligament repair with porcine metatarsal bones as substitute [8] and a good comparability towards the clinical situation. Pullout force in nonosteoporotic human bone and porcine bone was comparable in our study but is significantly higher as in osteoporotic human bone. To provide an adequate osteoporotic bone model with cancellous bone structure and thin cortex, the human cuboid was chosen, which is the

### Table 1

| Ultimate axial pullout load (N) mean ± SD | 2.7 HL screw | 3.5 NL screw |
|------------------------------------------|--------------|--------------|
| Composite first metatarsal | 1185 ± 225 | 175 ± 116 |
| Human nonosteoporotic first metatarsal | 791 ± 130 | 943 ± 304 |
| Porcine cuboid | 744 ± 185 | 910 ± 140 |
| Human nonosteoporotic cuboid | 567 ± 242 | 852 ± 281 |
| Human osteoporotic cuboid | 167 ± 78 | 185 ± 113 |
| **Axial stiffness (N/mm) mean ± SD** | | |
| Composite first metatarsal | 1241 ± 172 | 1284 ± 161 |
| Human nonosteoporotic first metatarsal | 679 ± 122 | 807 ± 323 |
| Porcine cuboid | 309 ± 88 | 666 ± 226 |
| Human nonosteoporotic cuboid | 399 ± 224 | 620 ± 205 |
| Human osteoporotic cuboid | 177 ± 88 | 204 ± 121 |

### Table 2

The $p$ values of the respective comparisons of ultimate axial pullout force and axial construct stiffness of 2.7 mm head locking screws.

| $p$ values stiffness (2.7 mm screws axial pullout) | MT I composite | MT I nonosteoporotic | Cuboid porcelain | Cuboid nonosteoporotic | Cuboid osteoporotic |
|-----------------------------------------------|----------------|----------------------|------------------|------------------------|---------------------|
| $p$ values maximum load (2.7 mm screws axial pullout) | MT I composite | $<0.01$ | $<0.01$ | $<0.01$ | $<0.01$ |
| MT I nonosteoporotic | $<0.01$ | $<0.01$ | 0.02 | $<0.01$ |
| Cuboid porcelain | $<0.01$ | n.s. | n.s. | $<0.01$ |
| Cuboid nonosteoporotic | $<0.01$ | n.s. | n.s. | n.s. |
| Cuboid osteoporotic | $<0.01$ | $<0.01$ | $<0.01$ | 0.047 |

### Table 3

The $p$ values of the respective comparisons of ultimate axial pullout force and axial construct stiffness of 3.5 mm nonlocking screws.

| $p$ values stiffness (3.5 mm screws axial pullout) | MT I composite | MT I nonosteoporotic | Cuboid porcelain | Cuboid nonosteoporotic | Cuboid osteoporotic |
|-----------------------------------------------|----------------|----------------------|------------------|------------------------|---------------------|
| $p$ values maximum load (3.5 mm screws axial pullout) | MT I composite | n.s. | $<0.01$ | $<0.01$ | $<0.01$ |
| MT I nonosteoporotic | n.s. | n.s. | n.s. | $<0.01$ |
| Cuboid porcelain | n.s. | n.s. | n.s. | $<0.01$ |
| Cuboid nonosteoporotic | n.s. | n.s. | n.s. | 0.03 |
| Cuboid osteoporotic | $<0.01$ | $<0.01$ | $<0.01$ | $<0.01$ |
central structure in the so-called “nutcracker fracture,” and because of its almost completely cancellous architecture, osteosynthesis is often difficult. Using the cuboid, we were able to point out differences in screw fixation in osteoporotic and nonosteoporotic bone. Since composite bones of the cuboid for biomechanical testing are not available and composite bones from the same production line provide similar mechanical characteristics, only first metatarsal bones were investigated and additionally compared to nonosteoporotic human first metatarsals. The low mechanical strength of osteoporotic human bone could not be mimicked by any of the substitutes tested. Animal bone is not suited as osteoporotic bone substitute, since osteoporosis is unknown in other vertebrates than humans. Although the bones were categorised by age, apparent BMD did not differ significantly

Table 4 Ultimate (maximal) shear force and construct stiffness in shear direction of 2.7 mm head locking screws (HL) and 3.5 mm nonlocking screws inserted into porcine and human cuboid bone. Mean values and standard deviation (SD) are given.

|                          | 2.7 HL screw | 3.5 NL screw |
|--------------------------|--------------|--------------|
| Ultimate shear load (N)  |              |              |
| mean ± SD                |              |              |
| Porcine cuboid           | 431 ± 155    | 278 ± 99     |
| Nonosteoporotic cuboid   | 374 ± 137    | 207 ± 68     |
| Osteoporotic cuboid      | 169 ± 72     | 49 ± 26      |
| Shear stiffness (N/mm)   |              |              |
| mean ± SD                |              |              |
| Porcine cuboid           | 305 ± 83     | 77 ± 27      |
| Nonosteoporotic cuboid   | 215 ± 46     | 71 ± 38      |
| Osteoporotic cuboid      | 285 ± 79     | 28 ± 19      |

Figure 2  Load-displacement curves of axial pullout testing using 2.7 mm head locking screws. Curves of one representative specimen per group are shown.
HL = head locking.

Figure 3  Load-displacement curves of axial pullout testing using 3.5 mm nonlocking screws. Curves of one representative specimen per group are shown.
NL = nonlocking.
The nonsignificant difference in apparent BMD between nonosteoporotic and osteoporotic human bone is attributed to the higher standard deviation of these values in the osteoporotic human bone group compared to the nonosteoporotic human and porcine bone group, reflecting the reality in biomechanical tests using fresh frozen human bone samples [3,6].

The inhomogeneity of bone density between the donors, especially in advanced donor age, may additionally influence the study results [6]. Using porcine bone as substitute, a relatively homogeneous BMD could be expected, as shown by the correspondent lower standard deviation. As known from previous studies [12], porcine bone exhibited a significantly higher apparent BMD compared to nonosteoporotic and osteoporotic human bone which is not necessarily reflected in higher stress resistance for porcine bone in the mechanical tests. The BMD provides a rough estimation but not adequately characterises the mechanical bone strength [12].

To allow a realistic comparability of the synthetic composite metatarsal bones to nonosteoporotic human bone, the nonosteoporotic human first metatarsal bone group was added. In both groups, screws are anchored bicortically in the shaft cortices. However, screw pullout force was highest in synthetic composite metatarsal bone with significance for 2.7 mm screws, making this substitute not recommendable without restrictions. Owing to their increased fixation capacity, composite bones will shift the failure site from the bone-implant interface to the implant itself, rendering a clinical interpretation of the results difficult.

Figure 4  Load-displacement curves of shear testing using 2.7 mm head locking screws. Curves of one representative specimen per group are shown. HL = head locking.

Figure 5  Load-displacement curves of shear testing using 3.5 mm nonlocking screws. Curves of one representative specimen per group are shown. NL = nonlocking
Conclusion

Respecting the limited availability of nonosteoporotic human bone specimens, porcine bone exhibits screw pullout and screw shear forces close to nonosteoporotic human bone, mimicking these two mechanical parameters more appropriate than synthetic composite bone.

Conflicts of interest statement

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jot.2018.06.001.

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