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ORIGINAL ARTICLE

Q1
Axial and shear pullout forces of composite, porcine and human metatarsal and cuboid bones☆

Q7
Mark Lenz [a,b,*,☆☆], Boyko Gueorguiev [a,☆☆], Juan B.Gerstner Garces [c], Michael P. Swords [d], Stefan Rammelt [e], Gunther O. Hofmann [b], Ivan Zderic [a], Manuela Ernst [a], Robert Geoff Richards [a], Andrew K. Sands [f]

[a] *AO Research Institute Davos, Clavadelerstrasse 8, CH-7270 Davos-Platz, Switzerland*
[b] *Dept. of Trauma, Hand and Reconstructive Surgery, University Hospital Jena, Am Klinikum 1, D-07747 Jena, Germany*
[c] *Centro Medico Imbanaco of Cali, Carrera 38 A, No. 5 A 100 Con 233, Cali, Colombia*
[d] *Mid-Michigan Orthopaedic Institute, 830 West Lakee Lansing Road Suite 190, East Lansing, MI 48823, USA*
[e] *University Hospital Carl Gustav Carus, Fetscherstrasse 74, 01307 Dresden, Germany*
[f] *New York Presbyterian - Lower Manhattan Hospital, 170 William Street, New York, NY 10038, USA*

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Abstract *Objectives:* The varying mechanical properties of human bone have influence on the study results. Pullout and shear forces of human bone were compared to different substitutes to evaluate their suitability for biomechanical studies.
Methods: After bone mineral density (BMD) determination, axial pullout tests were performed with cortical 3.5 mm nonlocking (NL) and 2.7 mm head locking (HL) screws on human, porcine and composite bones. Porcine and human constructs were additionally loaded in shear direction.
Results: Apparent BMD was significantly lower in osteoporotic (159 mgHA/ccm ± 56) and non-osteoporotic (229 mgHA/ccm ± 25) human bone than that in porcine bone (325 mgHA/ccm ± 42; $p < 0.01$). Axial construct stiffness and ultimate pullout force of porcine bone

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* Corresponding author. Department of Trauma, Hand and Reconstructive Surgery, University Hospital Jena, Am Klinikum 1, D-07747 Jena, Germany.
E-mail addresses: lenzmar@web.de (M. Lenz), boyko.gueorguiev@aofoundation.org (B. Gueorguiev), jbgerstner@me.com (J.B.foot.trauma@gmail.com (M.P. Swords), Stefan.Rammelt@uniklinikum-dresden.de (S. Rammelt), gunther.hofmann@med.uni-jena.de (G.O. Hofmann), ivan.zderic@aofoundation.org (I. Zderic), manuela.ernst@aofoundation.org (M. Ernst), geoff.richards@aofoundation.org (R.G. Richards), aksands@gmail.com (A.K. Sands).
☆☆ Dual first authorship.

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(NL: 666N/mm ± 226, 910N ± 140; HL: 309N/mm ± 88, 744N ± 185) was significantly different from composite bone (NL: 1284N/mm ± 161; 1175N ± 116; HL: 1241N/mm ± 172, 1185N ± 225) and osteoporotic human bone (NL: 204N/mm ± 121, 185N ± 113; HL: 201N/mm ± 65; 189N ± 58) but not from nonosteoporotic human bone (NL: 620N/mm ± 205, 852N ± 281; HL: 399N/mm ± 224; 567N ± 242). Porcine bone exhibited an ultimate shear force (NL: 278N ± 99; HL: 431N ± 155) comparable to nonosteoporotic human bone (NL: 207 ± 68: HL: 374N ± 137).

Conclusion: Screw pullout and shear forces of porcine bone are close to nonosteoporotic human bone.

Q3

The translational potential of this article: Human bone specimens used in biomechanical studies are predominantly of osteoporotic bone quality. Conclusions on nonosteoporotic human bone behaviour are difficult. Alternatives such as porcine bone and composite bone were investigated, and it could be shown that screw pullout and screw shear forces of porcine bone are close to nonosteoporotic human bone.

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.

Q4

Bone quality is reduced or even osteoporotic in most of the human bone specimens, especially the female ones, since donor age is almost 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 compared to human bone specimens [9,10]. Porcine bone available in the slaughterhouse is collected mainly from relatively young animals, not older than 0.5–2 years, having the potential to mimic human bone from young athletic individuals.

This study investigated the suitability of porcine bone and synthetic composite bone as human bone substitutes for biomechanical studies on fore and midfoot fixation techniques. Their mechanical properties and the bone mineral density (BMD) of porcine bone are compared to nonosteoporotic and osteoporotic human bone.

It is hypothesised that pullout and shear properties of porcine bone are closer to that of nonosteoporotic human bone than the pullout and shear properties of osteoporotic human bone specimens.

Materials and methods

Six surrogate large left first metatarsal fourth generation composite bones, designed for biomechanical testing (Sawbones Europe, Malmö, Sweden, reference number 3422), six porcine cuboids (mean donor age 8 month, acquired from local slaughtery), 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, Brüttisellen, 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.