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Research Paper

Biomechanical measurements of cortical screw purchase in five types of human and artificial humeri

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ABSTRACT

Humerus shaft fracture fixation is largely dependent on cortical screw purchase in host bone. Only 2 prior studies assessed cortical screw purchase in human humeral shafts, but were of very limited scope and did not fully assess humerus material properties. Also, no studies evaluated the human dried or artificial humeri both commercially available from Sawbones. Vashon, WA, USA. Therefore, present authors measured cortical screw purchase in human fresh-frozen (FF) ($n=19$), human embalmed (EM) ($n=18$), human dried (DR) ($n=14$), artificial "normal" (AN) ($n=13$), and artificial "osteoporotic" (AO) ($n=13$) humeri. Each humerus had 2 bicortical screws of 3.5-mm diameter inserted 20 mm apart through the shaft's anterior and posterior cortices. Absolute force, displacement, and energy for screw-bone interface failure were measured by screw pullout tests, afterwhich data were normalized by total surface area engaged at the screw-bone interface. For absolute force, AN humeri reached a higher load than EM ($p=0.001$) and AO ($p<0.001$) humeri, whilst AN humeri achieved lower normalized force than DR humeri ($p=0.018$). For absolute displacement, AO humeri achieved a lower level than FF humeri ($p=0.013$), whilst for normalized displacement AN humeri had lower levels than all other groups ($p\leq 0.005$) and AO humeri had lower values than EM humeri ($p=0.029$). For absolute and normalized energy, there were no statistical differences ($p\geq 0.066$). Human bone mineral density (BMD) ranged from 0.7 to 1.8 g/cm^2 and was linearly correlated to screw pullout parameters in 14 of 18 cases ($R=0.61$ to 0.96), whilst humerus age was not. Consequently, it is recommended that human fresh-frozen, human embalmed, and human dried humeri can be used interchangeably for cortical screw purchase, since they were statistically equivalent for all comparisons. However, artificial humeri were involved in all statistical differences observed and, thus, may not replicate cortical screw purchase in human humeri. To date, this is the most comprehensive study on cortical screw purchase in human and artificial humeral shafts.

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1. Introduction

The human humeral shaft experiences approximately 2% to 3% of all fractures (Pyati, 2006). If clinically indicated, surgical repair is done with extramedullary plates or intramedullary nails (Infante and Lindvall, 2008; Pyati, 2006). These implants are applied onto longbone with cortical screws, which can fail by a number of mechanisms, such as screw "toggling", screw pullout, screw fracture by bending or torsion, and screw stress risers that lead to failure of the host bone (Ansell and Scales, 1968; Fulkerson et al., 2006; Law et al., 1993; Merk et al., 2001). Consequently, cortical screw purchase is an important element in the mechanical stability of humerus shaft fracture fixation constructs.

Only 2 prior studies exist on cortical screw pullout in the human humeral shaft. One team in 1941 did pullout tests with two different metal screw types, but they did not report on the bone preservation method and used only one humerus (Lyon et al., 1941). The other more recent study did not report on the bone preservation method, the authors did not compute pullout energy, and they substantially tightened screws to pre-stress the screw-bone interface, but this does not permit accurate evaluation of humerus material properties for screw pullout (Tankard et al., 2013). Moreover, no prior investigators evaluated cortical screw purchase in either the dehydrated-disinfected human humeri or the Fourth Generation Composite Humeri both commercially available from Sawbones, Vashon, WA, USA (Sawbones). It would benefit researchers if "gold standard" fresh-frozen humeri could be substituted by these dehydrated-disinfected and/or artificial humeri, since they are less expensive, easier to obtain, have no biohazard, and have no special storage requirements versus fresh-frozen humeri. Cortical screw pullout in human and artificial femoral and tibial shafts has been previously measured (Stromsoe et al., 1993; Thiele et al., 2007; Zdero et al., 2007, 2009), but a new study on a variety of human and artificial humerus types is warranted.

The goal of this study, therefore, was to assess the material properties of human and artificial humeri via cortical screw pullout tests. Specifically, 5 types of humeri (i.e. human fresh-frozen, human embalmed, human dried, artificial "normal", and artificial "osteoporotic") were compared for absolute and normalized pullout force, displacement, and energy. This will help researchers better understand the material properties of human and artificial humeri and the role of cortical screw purchase for fracture fixation. To date, this is the most comprehensive study of cortical screw purchase in human or artificial humeral shafts.

2. Methods

2.1. Humerus characteristics

Fresh-frozen adult human humeri ($n=19$) were obtained from a tissue donation center after permission of the ethics board of the authors' institution. Specifications included age (average, 82.9±6.5 years; range, 66 to 93 years), gender (14 male, 5 female), and total length (average, 341.3±20.1 mm; range, 304 to 377 mm). Humeri were stripped of soft tissue, placed in plastic containers, stored for 3 years in a freezer at $-20\,^{\circ}$C, and thawed 18 h prior to testing.

Embalmed adult human humeri ($n=18$) were procured from the same aforementioned donation center. Specifications included age (average, 80.4±13.2 years; range, 60 to 97 years), gender (10 male, 8 female), and total length (average, 318.1±20.7 mm; range, 275 to 356 mm). Humeri were stripped of soft tissue and then stored in a plastic box for 3 years prior to testing.

Dried adult human humeri ($n=14$) were also obtained (Model #5513, Sawbones, Vashon, WA, USA) (Sawbones). They were disinfected using bleach and dehydrated by the supplier, and then stored for 3 years in a plastic container at room temperature. Dried humerus had total length measured (average, 320.5±9.5 mm; range, 301 to 334 mm), but no age or gender data were known.

Artificial adult-sized left humeri ($n=13$) were defined as having "normal" bone quality, with an intramedullary canal diameter of 9 mm starting at the proximal tip over a 285-mm length, which tapered down to 5.5 mm. Another group of artificial humeri ($n=13$) was "osteoporotic" with an intramedullary canal diameter of 13 mm starting at the proximal tip over a 285-mm length. Both humerus types were otherwise identical in properties and geometry and were purchased from the same supplier (Model #3404, Sawbones, Vashon, WA, USA) (Sawbones). Cortical bone (density$=1.64$ g/cm^3) was an epoxy resin matrix with e-glass fibers, cancellous bone (density$=0.27$ g/cm^3) was a "solid matrix" polyurethane foam, and length was 365 mm.

2.2. Bone mineral density (BMD)

The zone of each human humerus into which screws were to be inserted and extracted, i.e. the distal half of the shaft, was DEXA scanned with a Prodigy$^{\text{TM}}$ system equipped with enCORE software 8.80 (Lunar Corp, Madison, WI, USA). For the Prodigy$^{\text{TM}}$ system, donor weight and height aid in defining scan mode, although this was not important currently since little soft tissue was present. Standard scan mode, thus, was employed. Rice bags acted as soft-tissue surrogates and minimized scanning artifacts. For embalmed humeri, BMD from DEXA remains stable after bones are embalmed for several months (Lochmuller et al., 2001). No bony pathology was visible for any human humeri.

2.3. Screw insertion

For each humerus, 2 undersized, untapped, bicortical pilot holes of 2.5-mm diameter were drilled through anterior and posterior cortices at 20-mm and 40-mm locations distal to the midshaft. As done clinically, these undersized pilot holes were used to avoid humerus cracking and permit a tighter "bite" of screw threads into bone. The 20-mm distance between holes prevented proximity effects. A rigid steel guidewire was inserted (and removed) through the pilot hole in order to align the screw. Then, as usually done in orthopaedic surgery, a manual surgical screwdriver was used to insert each screw through the anterior cortex and then 3 to 4 threads beyond the far posterior cortex to ensure full