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Does cancellous screw insertion torque depend on bone mineral density and/or microarchitecture?

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ABSTRACT

During insertion of a cancellous bone screw, the torque level reaches a plateau, at the engagement of all the screw threads prior to the screw head contact. This plateau torque (T_{Plateau}) was found to be a good predictor of the insertion failure torque (stripping) and also exhibited strong positive correlations with areal bone mineral density (aBMD) in ovine bone. However, correlations between T_{Plateau} and aBMD, as well as correlations between T_{Plateau} and bone microarchitecture, have never been explored in human bone.

The aim of this study was to determine whether T_{Plateau}, a predictor of insertion failure torque, depends on aBMD and/or bone microarchitecture in human femoral heads.

Fifty-two excised human femoral heads were obtained. The aBMD and microarchitecture of each specimen were evaluated using dual X-ray Absorptiometry and micro-computed tomography. A cancellous screw was inserted into specimens using an automated micro-mechanical test device, and T_{Plateau} was calculated from the insertion profile.

T_{Plateau} exhibited the strongest correlation with the structure model index (SMI, $R=-0.82$, $p<0.001$), followed by bone volume fraction (BV/TV, $R=0.80$, $p<0.01$) and aBMD ($R=0.76$, $p<0.01$). Stepwise forward regression analysis showed an increase for the prediction of T_{Plateau} when aBMD was combined with microarchitectural parameters, i.e., aBMD combined with SMI (R^2 increased from 0.58 to 0.72) and aBMD combined with BV/TV and BS/TV (R^2 increased from 0.58 to 0.74).

In conclusion, T_{Plateau}, a strong predictor for insertion failure torque, is significantly dependent on bone microarchitecture (particularly SMI and BV/TV) and aBMD.

1. Introduction

Establishing the mechanical stability of the screw-bone construct is important for bone fracture repair (Battula et al., 2006; Helgeson et al., 2013; Mueller et al., 2013). Determining the optimal insertional torque in order to achieve the strongest possible screw-bone stability, while minimising the risk of screw stripping, is a challenge for surgeons. Surgeons judge the optimal insertion torque by feel, based on the bone's resistance during screw insertion (Tsuji et al., 2013). However, the judged optimal insertional torque may vary among surgeons, due to differences in their experiences and skills (Cordey et al., 1980; Siddiqui et al., 2005). Screw fixation strength, also referred as holding strength or pullout strength, is measured through laboratory mechanical testing, and is defined as the maximum axial force required to pull the screw out from the bone. Previous studies have compared the screw fixation strength as judged by the surgeon's perception of optimal insertion torque, with the fixation strength obtained from laboratory screw pull-out testing (Siddiqui et al., 2005; Cordey et al., 1980). Strong correlations were found in normal bone, however, in severely osteopenic bone, judgments differed among clinicians with different levels of experience (Cordey et al., 1980; Siddiqui et al., 2005).

Recently, in a study published by our group, by using an insertion micro-mechanical test rig, it was shown that during screw insertion of a cancellous screw into human, ovine and synthetic bone, the torque level reaches a plateau in the recorded insertion torque curve, at the engagement of all the screw threads prior to head contact (Reynolds et al., 2013). This plateau torque (T_{Plateau}) was found to be a strong predictor of the failure torque as determined from screw insertion tests until the screw stripped from the bone ($R>0.83$ for all investigated bone types). T_{Plateau} also showed strong positive correlations with areal bone mineral density (aBMD) in ovine samples, and bone density in synthetic

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bone samples ($R > 0.80$) (Reynolds et al., 2013). However, the correlations of T_{Plateau} and aBMD have yet to be explored in human bone, and to date, correlations between T_{Plateau} and bone microarchitecture have not been investigated.

The aBMD is a planar measurement of the bone mineral content (BMC) divided by the examined area using dual X-ray Absorptiometry (DXA), which can be obtained in clinics on the patient. Microarchitectural parameters, such as bone volume fraction (BV/TV), bone surface density (BS/TV), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp) trabecular number (Tb.N) and structure model index (SMI), refer to microscopic measurements of trabecular bone structures, obtained from micro-computed tomography (micro-CT), currently in use in preclinical research studies. Variations in microarchitectural parameters in human bone have shown to influence the stability of the screw-bone construct during laboratory failure testing (pull-out and push-in) (Poukalova et al., 2010; Yakacki et al., 2010; Mueller et al., 2013), as well as the bone strength during bone compressive testing (Öhman et al., 2007; Mueller et al., 2009; Cook et al., 2010; Perilli et al., 2012a). It could be expected that these microarchitectural parameters also influence T_{Plateau} during screw insertion in human bone.

Both the aBMD and bone microarchitecture vary both between and within patients. In some cases, aBMD measurements of the patient could be available prior to orthopaedic surgery, and, with future technological developments perhaps also measurements of the bone microarchitecture. If any of these bone parameters were predictive of T_{Plateau}, then these could also be used to predict failure torque in order to minimise the phenomena of over tightening during screw insertion. Therefore, it is important to study which and how these aBMD and microarchitectural variations do affect T_{Plateau} during screw insertion, since they could then be used in the prediction of optimal insertion torque in a patient-specific context.

The aim of this study was to investigate, for the first time, whether T_{Plateau}, a predictor of bone failure torque as measured during screw insertion, depends on aBMD or on bone microarchitectural parameters, or on their combination, in human femoral heads.

2. Materials and methods

2.1. Human bone samples

Fifty-two femoral heads, retrieved from hip surgery (21 females, 24 males, mean (SD) age = 76.6 (10.2) years) and from cadavers (1 female, 6 males, age = 82.1 (7.4) years), were used. The samples were provided by SA Pathology in Adelaide. Ethics approval was obtained from the local Human Research Ethics Committee. For preparation, the excised femoral head specimens were cut at the femoral neck to retain a minimum head height of 35 mm to provide sufficient depth and access for screw insertion (Fig. 1). Specimens were individually wrapped in gauze that was kept moistened with saline solution, placed in labelled ziplock bags and stored at −20 °C until the time of testing. Specimens were thawed for 24 h prior to testing.

2.2. Measurement of aBMD using DXA

Measurements of aBMD of the excised femoral heads were performed with a DXA scanner (GE Lunar Prodigy, Madison, WI, USA). The femoral heads were placed in anterior–posterior orientation on polyoxymethylene boards (Delrin®) (DuPont, Wilmington, Delaware, USA) supplied with the scanner, for simulating soft tissue (Farquharson and Speller, 1997). X-ray exposure was selected at 1.8 μGy, to gain optimum signal to noise ratio (Kiebzak et al., 1999; Bogden et al., 2008; Daley et al., 2010). At the completion of the scan, GE enCORE software (version 13.60, GE Healthcare Lunar, Madison, Wisconsin, USA) was utilised for the evaluation of BMC (measured in g) and bone area (measured in cm^2), from which aBMD was calculated (g/cm^2). The bone area within the DXA image was defined as a region of interest with size and shape adapted via software to the morphology of the femoral head, by an expert radiologist.

2.3. Screw insertion

Each femoral head specimen was subjected to one screw insertion at the centre of the cut surface. A partially threaded aluminium cancellous screw (screw length 45.5 mm, outer thread diameter 7.0 mm, inner thread diameter 5.2 mm, thread length 16.5 mm, thread pitch 2.0mm), fabricated in-house to replicate a current orthopeadic cancellous screw (Catalogue no. 7110-7050, Smith and Nephew, London, UK), was used. Aluminium was used as screw material instead of the original titanium to avoid artifacts during bone-screw imaging with high resolution micro-CT. The screw was first manually inserted by means of a benchtop drill press through a pilot hole of 5.2 mm diameter as recommended by the screw manufacturer (Catalogue no. 7111-9106, Smith and Nephew, London), leaving a small gap (2 mm to 3 mm) between the screw head and bone. The bone-screw assembly was then transferred to a miniature version of a micro-mechanical test device (Cleek et al., 2007; Reynolds et al., 2013), for automated insertion of the screw beyond head contact, all of which was performed inside a micro-CT scanner (Skyscan model 1076, Skyscan, Kontich Belgium). The automated micro-mechanical test device was specially designed and constructed at Flinders University, to enable the screw insertion to be performed inside the micro-CT system. The test device was interfaced with a computer for controlling and monitoring of the screw insertion parameters in real time, such as torque, compression and screw rotation from outside of micro-CT, whilst performing micro-CT imaging of the bone-screw, through a radiolucent sample holder (Fig. 2a). The insertion torque (measured in mNm), the compression under the screw head (measured in N) and the screw rotation (measured in degrees) were captured through the torque controller (TRT-100, Transducer Techniques, Temecula, California, USA), compression transducer (THB-250-S, Temecula, California, USA) and motor/encoder (Part no. 315360, Maxon Motor Ag, Sachseln, Switzerland) of the test device, respectively (Reynolds et al., 2013). A micro-CT scan of the bone-screw construct was performed immediately after the automated insertion of the screw was completed, without removing the construct from the scanner (Fig. 2b).

2.4. Description of screw insertion

At the initial phase of screw insertion, there was a sharp increase in torque, indicating that the screw threads began to gain purchase within the bone (Fig. 3a). Once all screw threads were fully purchased with the bone, prior to head contact, the torque stabilised, reaching a plateau. T_{Plateau} was calculated from the average of twenty torque data points prior to head contact within the plateau region (Fig. 3a).

The compression under the screw head is zero prior to head contact after which the compression linearly increases (Fig. 3b). Head contact was defined as occurring once the compression exceeded the value of 2 N. Further insertion resulted in screw tightening, where both torque and compression rose linearly (bone elastic behaviour). When the torque reached its peak, bone failure occurred

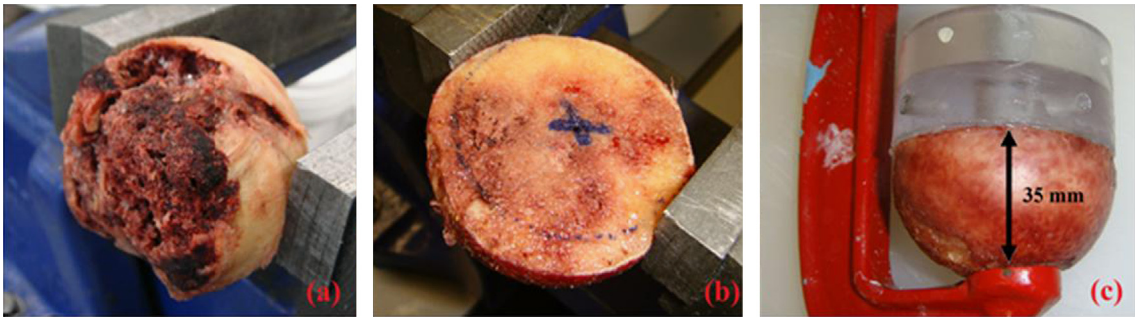

Fig. 1. Various stages of specimen preparation (a, b and c). Bone thickness of 35 mm was retained for sufficient penetration depth of the threaded section of screw.