

Drilling resistance: A method to investigate bone quality

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Purpose: Bone drilling is a major part of orthopaedic surgery performed during the internal fixation of fractured bones. At present, information related to drilling force, drilling torque, rate of drill-bit penetration and drill-bit rotational speed is not available to orthopaedic surgeons, clinicians and researchers as bone drilling is performed manually. *Methods:* This study demonstrates that bone drilling force data if recorded in-vivo, during the repair of bone fractures, can provide information about the quality of the bone. To understand the variability and anisotropic behaviour of cortical bone tissue, specimens cut from three anatomic positions of pig and bovine were investigated at the same drilling speed and feed rate. *Results:* The experimental results showed that the drilling force does not only vary from one animal bone to another, but also vary within the same bone due to its changing microstructure. Drilling force does not give a direct indication of bone quality; therefore it has been correlated with screw pull-out force to provide a realistic estimation of the bone quality. A significantly high value of correlation ($r^2 = 0.93$ for pig bones and $r^2 = 0.88$ for bovine bones) between maximum drilling force and normalised screw pull-out strength was found. *Conclusions:* The results show that drilling data can be used to indicate bone quality during orthopaedic surgery.

Key words: bone drilling, orthopaedic surgery, screw pull-out strength, bone mineral density, bone quality

1. Introduction

Bone strength and its measurement have been a matter of debate for several years. Bone strength is used as a means to evaluate the risk of bone fracture; similar to metals, any mechanical property of the bone which gives the measurement of its internal stresses produced due to loading will give a measure of bone strength [26], [27]. Bone fracture resistance depends on both bone quantity and bone quality; it is defined largely as all geometric, micro-architectural, and material factors (e.g., collagen crosslinking, mineralization, micro-cracks) that contribute to the whole-bone fracture resistance [3], [4], [11].

Mechanical properties of bone give a direct measurement of bone quality and are evaluated using de-

structive mechanical testing methods [5], [22]. Mechanical testing allows direct assessment of a range of mechanical properties across multiple length scales. At the macroscopic level, whole-bone testing allows assessment of bone structural properties such as structural stiffness and strength [6], [23]. At smaller length scales, material testing techniques enable measurement of the intrinsic properties of the tissue such as elastic modulus and ultimate stress [12], [29]. Although the determination of the mechanical properties plays an important role in the evaluation of bone strength, it depends on many factors related to the specimen, testing condition and storage method. Mechanical testing requires a large amount of bone samples, and also meticulous specimen preparation due to the intricate bone structure. However, as the specimen is removed from the bone, testing is carried out under

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non-physiologic boundary conditions. To a certain extent, the size of the specimen represents a limit in terms of accuracy that can be achieved by mechanical testing. Therefore, there is a limit in the clinical value of using such mechanical method in the evaluation of bone quality.

Bone densitometry is the most commonly used method in clinics to estimate the patient's bone strength through BMD (Bone Mineral Density) measurements [26], [29]. However, non-site specific BMD measurements give a less accurate prediction of bone strength, as compared to site specific BMD measurements [12], [15], [20]. Furthermore, BMD is the measure of bone mineral quantity and does not fully reflect bone quality [7].

Previous studies [8], [20] suggested that bone drilling data, if recorded and analysed, could be used to predict the quality of bone. In this study, we have investigated the efficacy of using drilling force data for the indication of bone quality. In the first part of this study, the variability of the drilling force at different anatomic positions is established. The second part of the study is focused on correlating the drilling force with the screw pull-out force. The correlation between the normalised screw pull-out force (force/thickness) and drilling force was investigated to establish the effectiveness of using drilling force to represent a material property/bone quality.

2. Materials and methods

2.1. Specimen preparation

Bovine and pig cortical bone femurs were used in this research. The bones were obtained from a local butcher and were excised into rectangular shaped samples according to three anatomic positions (Anterior, Posterior, and Medial) as shown in Fig. 1. The bone specimens were stored frozen at $-10\text{ }^{\circ}\text{C}$ and were allowed to thaw for 24 hours just before the tests were carried out. The bovine bone pieces were 75–90 mm in length with an average thickness of the cortical wall of 7–9 mm, and the pig bone pieces were 30–40 mm in length with an average thickness of cortical wall of 3–5 mm. A total of twelve test specimens were prepared from the bone pieces and every specimen was divided into seven and five equal sections for bovine and pig, respectively, each accommodating approximately four drilled holes. The main stages of specimen preparation are shown in Fig. 1b.

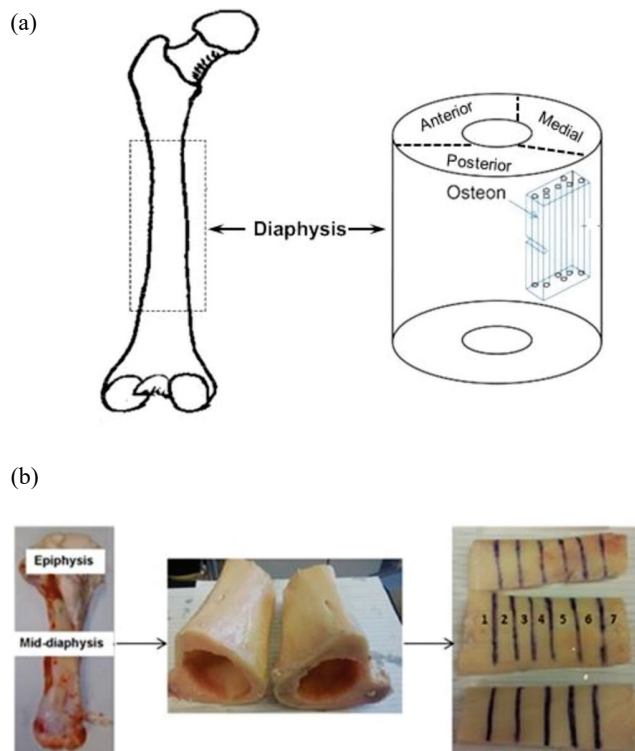


Fig. 1. (a) Femur anatomic positions; (b) preparation of bone specimens

2.2. Experimental setup

An electromechanical test rig, shown in Fig. 2a, was designed to carry out drilling and screw pull-out experiments. The rig was designed for drilling, screw tapping, screw insertion and screw pull-out. It is composed of a counterbalanced inner frame which houses a servo DC motor drive system for drilling and a stepper motor unit for screw tapping and insertion. The latter was inactive during the drilling operation and is engaged (with the servo DC system disengaged) during the screw pull-out experiments. The inner frame is guided vertically using linear bearings and counterbalanced using a pulley and weights arrangement.

For the drilling experiments the test specimens were placed on the Specimen Mounting Assembly composed of a plate supported on a force transducer (model no. LCM101-10, Omega Engineering, Ltd., UK) which measures the drilling force during the drilling experiments. In addition, the Specimen Mounting Assembly is mounted on a rotary table supported on a ball bearing assembly to allow rotation of the specimen mounting plate. The mounting arrangement is shown in Fig. 2b. The rotary movement of the rotary table is restricted using a strain gauged (Wheatstone bridge) cantilever beam; thus giving a measure of the drilling torque. Drill-bit guide bushings were

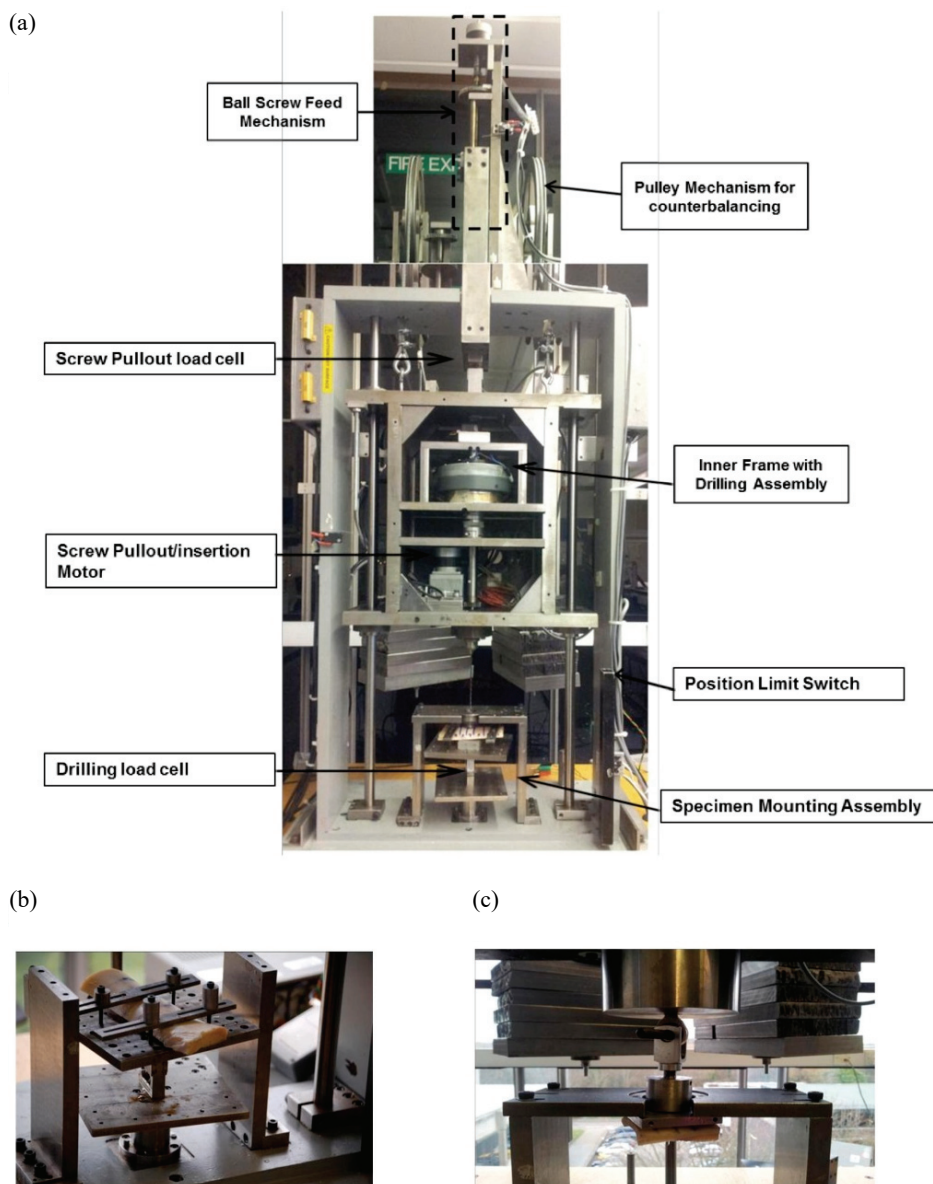


Fig. 2. (a) Test rig; (b) specimen mounting for drilling; (c) specimen mounting for screw pullout

used to guide the drill-bit and ensure that it is driven into the specimen at a 90° angle. The drilling force was recorded at a sampling rate of 500 Hz. A 12-bit, eight channel data acquisition system was used for the data acquisition (model no. USB-1208FS, Measurement Computing Corp. UK). A constant drill feed rate for the drilling experiments, and constant screw pull-out rate for the screw pullout experiments, were provided by a ball screw feed mechanism which was powered by a stepper motor. An encoder was mounted on the ball screw to directly record its rotation, which is converted into drill-bit (or screw) displacement and linear speed. During drilling and screw pull-out experiments, the drill-bit feed rate and screw pull-out rate were recorded via RS232 interface and displayed on the computer screen. Drilling was carried out at

a feed rate of 150 mm/min, based on the assumption made about the approximate drilling time that a surgeon would take to perform drilling in orthopaedic surgical procedures. The required drilling speed was provided by a DC servo motor with speed control. Drilling in the cortical bone specimens were carried out at a drilling speed of 800 rpm, using diameter of 2.5 mm industrial drill-bits (Model A9762.2X95 Dormer UK). This speed was chosen to reduce the generation of high temperature during drilling. All the experiments were performed at room temperature without cooling as in real orthopaedic surgery. The minimum number of holes to be drilled into each section of cortical bone specimen, for the study to be 95% statistically significant, was calculated using the sample size calculation equation presented by Dell

et al. [10]. A sample size of three was obtained. This was based on the calculated drilling force standard deviation value of 0.5 N and a margin of error of 0.65 N for the experimental setup using a homogenous material.

For the screw pull-out test involves hole tapping, screw insertion and then screw pull-out. The screw is connected to the screw pull-out attachment assembly as shown in Fig. 2c. A surgical cortical screw (Model No 204.045, Synthes., UK) was used for the pull-out experiments on the femur cortices. The key dimensions of surgical screws used were measured using an optical microscope of 1 μm least count and are given in Table 1. Tapping of the pilot holes (2.5 mm diameter) was done using a tap supplied by the manufacturer for the corresponding screw type used in this study. Both tapping and screw insertion were done at a constant speed of 10 rpm, with a constant axial force of 1.14 Kgf in accordance with ASTM F543-02 [2]. The load is applied by releasing the inner frame from the ball screw mechanism assembly, making it free to move up/down with practically no additional force, and then a weight corresponding to 1.14 Kgf is removed from the counterbalancing system. For the screw pull-out part of the process, the inner frame is fixed to the ball screw mechanism via the screw pull-out load cell (LC101-2000, Omega Engineering Ltd., UK). A constant pull-out rate of 5 mm/min was used in accordance with ASTM F543-02 [2]. Apparent densities for all specimens were determined using the in-vitro Archimedes' principle. The values are listed in Table 2.

Table 1. Cortical screw profile

Major diameter	3.45 mm
Core diameter	2.38 mm
Pitch	1.25 mm
Thread angle	40°

Table 2. Apparent bone sample densities with standard variation

	Anterior	Posterior	Medial
Bovine	2.2 \pm 0.03	2.0 \pm 0.04	2.1 \pm 0.05
Pig	2.1 \pm 0.05	2.0 \pm 0.03	2.05 \pm 0.06

3. Results

A typical profile of the drilling force with respect to the drill-bit displacement for a single hole was ob-

tained as shown in Fig. 3. The drilling profile is divided into four zones. Zone I shows the penetration of the drill-bit, which can be seen by a sharp rise in the drilling force. Zone II shows the start of material removal by chisel edge and main cutting edge with gradual rise in force upon drill-bit entry into the anterior cortex. The drill-bit is fully engaged at the end of zone II and throughout zone III. Zone IV shows a gradual drop in force as the drill-bit exits the cortex. Similar drilling force profiles having different drilling force magnitudes were observed for both bovine and pig at all the anatomic positions considered in this study. The drilling force referred to in the discussion below is the average maximum drilling force calculated in zone III.

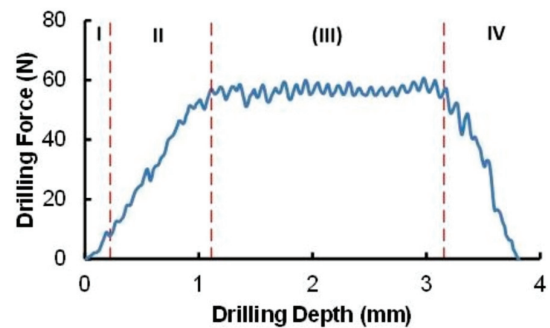


Fig. 3. Drilling force profile in pig cortex at feed rate of 150 mm/min and speed of 800 rpm

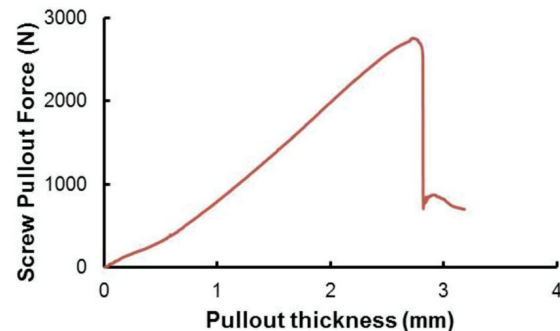


Fig. 4. Screw pullout force profile in bovine bone at pullout rate of 5 mm/min

The typical screw pull-out force profile for single cortex of bovine bone is shown in Fig. 4. This curve shows gradual increase of the pull-out force up to a peak force and then a sudden drop of force due to thread failure. A slight rebound of the screw, observed at the end of the thread failure and shown at the end of the force profile, is due to a sudden movement of screw and test rig immediately after failure. A similar type of curve is observed for each sample with different magnitudes and thickness.

3.1. Bone variability and drilling force

Drilling profiles for three anatomic cortices at the same feed rate and speed are illustrated in Fig. 5. The anterior quadrant has the highest drilling force, while the posterior quadrant has the lowest. The difference between the highest and lowest values of drilling force within the posterior quadrant of pig cortex for

different samples was 20 N. This shows that the drilling force is position sensitive, and is linked to the mechanical properties and composition of different anatomic position. Figure 6 exhibits the comparison of the drilling force at feed rate of 150 mm/min and rotational speed of 800 rpm for different anatomic positions of bovine and pig femur bones. The average maximum thrust force of bovine and pig femur were found to be 75 ± 5 N and 57 ± 10 N

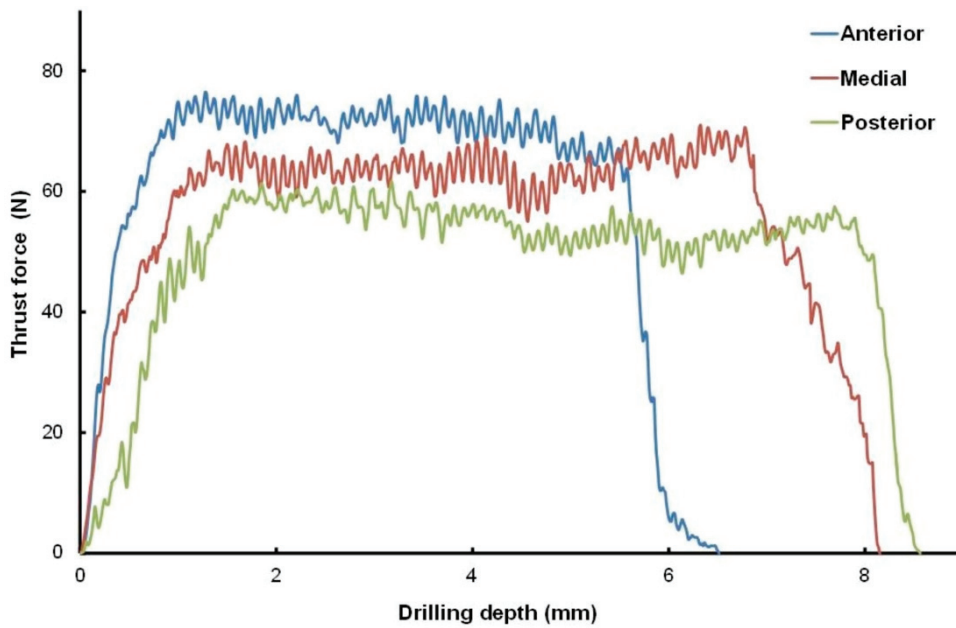


Fig. 5. Drilling force profiles of bovine cortex at different anatomic positions (feed rate = 150 mm/min and rotational speed = 800 rpm)

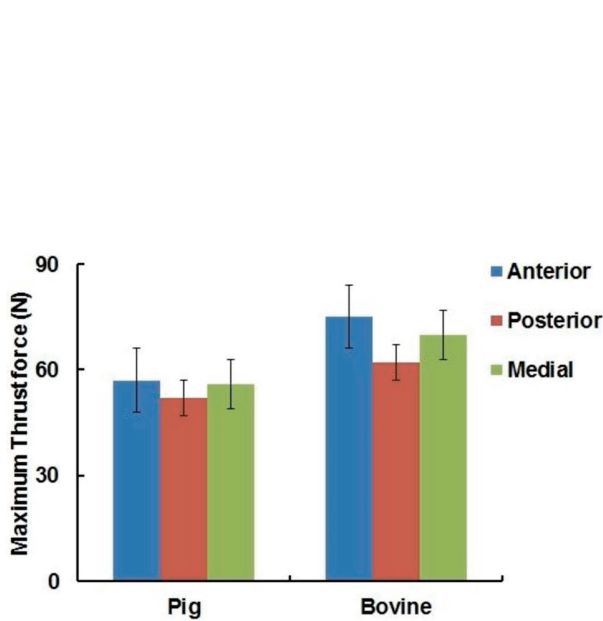


Fig. 6. Comparison of drilling forces for different cortex positions of bovine and pig femoral cortical bone tissues (Max standard deviation ± 5)

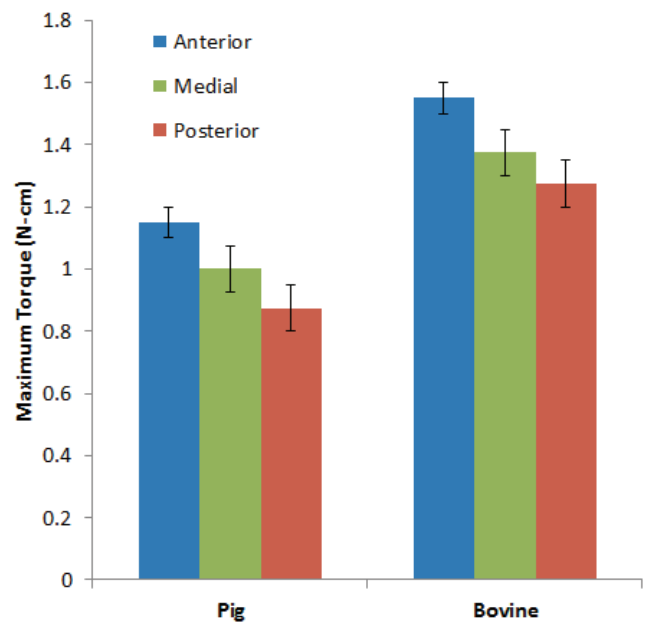


Fig. 7. Comparison of maximum torque for different cortex positions of bovine and pig femoral cortical bone tissues with standard deviation

for the anterior portion, 70 ± 4 N and 56 ± 5 N for the medial portion, and 62 ± 5 N and 52 ± 5 N for the posterior portion, respectively. The thrust force of bovine femur at these drilling conditions is greater than pig femur by 31% in the anterior portion, by 25% in the medial portion, and by 19% in the posterior portion. Similarly, Fig. 7 shows the values of torque at feed rate of 150 mm/min and rotational speed of 800 rpm for different anatomic positions of bovine and pig femur bones and presents that the values of torque also vary across different anatomical positions. The torque for bovine and pig femur were found to be 1.5–1.6 N·cm and 1.1–1.2 N·cm for the anterior portion, 1.3–1.45 N·cm and 0.9–1.1 N·cm for the medial portion, and 1.2–1.35 N·cm and 0.8–0.95 N·cm for the posterior portion, respectively. The bone density increases from posterior to interior

by 9% and 4.7% for bovine and pig, respectively (as shown in Table 2). However, the increase of force from posterior to interior is 17% and 8.7%, respectively. Furthermore, the increase in torque for posterior to interior is 25% and 33% in bovine and pig, respectively.

3.2. Relationship between drilling force and screw pull-out force

The maximum screw pull-out force depends upon the specimen thickness; therefore it was normalised by dividing the force by the specimen thickness. Figure 8a, b shows the relationship between drilling force and normalised screw pull-out force. A correlation coefficient of $r^2 = 0.9344$ and $r^2 = 0.8896$ was

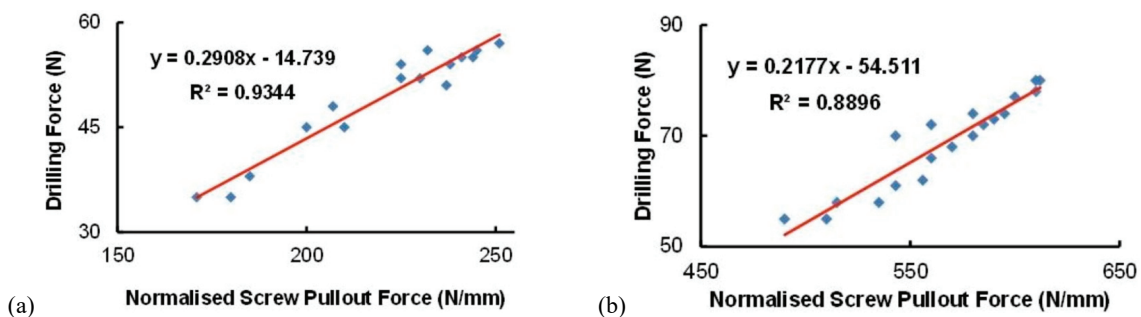


Fig. 8. Correlation between drilling force and normalised screw pullout force: (a) pig cortex, (b) bovine cortex

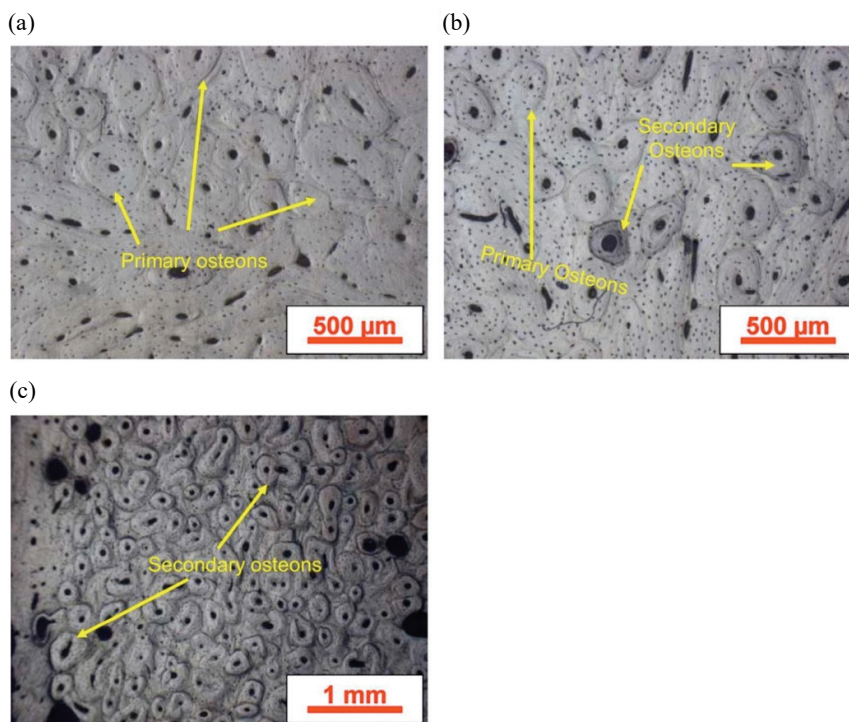


Fig. 9. Representative microstructural features of different cortex positions: (a) anterior; (b) medial; (c) posterior [15]

found for pig and bovine cortices, respectively. This indicates that there is a strong relationship between the average drilling force and normalised screw pull-out force in pig and bovine cortices. The pull-out force increases with increase of thickness, because the number of thread contacts increases with increase in thickness. The average thickness of the bone samples used for testing was between 3 mm to 5 mm for pig bones and between 6 mm to 9 mm for bovine bones. This is deduced from the drilling force profiles. The pitch of the screw used for pull-out testing was 1.25 mm. Therefore, the numbers of screw threads engaged into the bone specimens were approximately 3 for pig bones and 5 for the bovine bones.

4. Discussion

As could be seen in Fig. 5 that the results are in line with earlier studies, that demonstrated a variation in the mechanical properties around the human femoral shaft; bone from posterior quadrant is more porous and weaker than other quadrants [17], [24], [25]. This weakness is associated with the presence of Haversian systems (secondary osteons), and these can appear in two different ways: first, reduction in the amount of bone, and, secondly, reduction in the amount of calcium [9]. The reason for different drilling forces at different cortex positions shown in Fig. 6 stems from the non-uniform in-vivo loading experienced by bone due to body weight and muscle forces; and, according to the Wolf's Law [28], it adapts itself to be stiffer and stronger in positions subjected to higher loads. Present results reveal that anterior and medial parts of the femur were subjected to the highest loading while posterior to the lowest. These results are consistent with other investigation on bone quality in literature [16]. Simin et al. [16] in their recent microstructural investigation of bone showed that the anterior portion of cortex is predominantly occupied by primary osteons; the medial portion has a mixture of both primary and secondary osteons; whereas the posterior portion predominantly consists of secondary osteon together with interstitial matrix as shown in Fig. 9. This difference in microstructure of various portions of a bone leads to variation in strength at its different portions making anterior and posterior portions strongest and weakest, respectively. A similar pattern of variation in bone quality is observed in the present study. From the experimental results presented in Section 3.1, it is established that drilling is a good predictor of bone quality. This study shows that the bone density is only

one of the many contributors to the bone quality and strength. Additionally, it shows that the effect of density is not directly proportional to the thrust force and torque in both pig and bovine. Cefalu [7] in his investigation showed that bone strength does not only depend upon bone mass or bone quantity but also depends on bone quality. The factors which contribute to the bone quality include bone architecture and morphology, degree on mineralisation, accumulated fatigue damage and property of intrinsic organic matrix. Therefore, estimating bone health using densitometry techniques could lead to a less accurate prediction of patients bone quality especially in the case of osteoporotic patients.

The screw pull-out test also gives the shear property of the bone, thus provides direct information on the bone quality; however it cannot be measured in-vivo. Previous studies [13], [18] tried to establish correlation between screw pull-out force and bone densitometer measurements. However, practically in clinics it is not possible to take site specific bone density measurements at the fracture site. Thus, using the non-site specific bone density measurements would lead to a less accurate prediction of the bone strength. Similarly, the shear strength of bone can be calculated by using screw pull-out force [21]. Furthermore, Mauch and Lauderbaugh (1990) [17] presented a model in which the drilling force is function of the yield shear strength. Chagneau and Levasseur (1992) [8] proposed a technique called dynamostratigraphy for the mechanical testing of bone. In this technique, the drilling force and the drilling torque are continuously measured along the drill depth at constant rotational speed and feed rate. This technique is useful in finding the change of structure, mechanical property and the density variation of the bone along the drilling path. They applied dynamostratigraphy to study the morphology of bone structure and mechanical resistance of head of human cadaver femur bone using a 4 mm diameter three-lipped drill bit. The mechanical resistance of bone depends on the density, state of hydration, structure, material property and mineral content of the bone. To compare the mechanical resistance of bone, the hardness testing of the right side femoral head was conducted and the left side was used for dynamostratigraphy. When compared to results from drilling tests, higher forces were obtained by punching. Correlation between punching, drilling force and a theoretical model to estimate the drilling force was not presented. In present study, screw pull-out test has been conducted using same drilling holes which gave site specific results. Allotta et al. [1] proposed an analytical model for calculating the drilling force, and

they suggested that the value of specific cutting energy is five times the value of ultimate tensile strength of bone, which is not supported in the literature.

5. Conclusions

In this paper, the efficacy of using drilling force data has been investigated, if recorded in-vivo during the repair of bone fractures, to predict the strength or quality of the bone. A comprehensive experimental work was carried out, and the following observations were made in this study.

- Bone drilling force is different for different anatomic positions of the femur. Random and heterogeneous arrangements of the microstructure contribute to a wide range of drilling profiles/mechanical properties observed in the literature.
- A strong correlation between drilling force and normalised screw pullout force was produced for both bovine and pig femoral cortices, noting that the pullout force is directly proportional to shear strength of bone.
- Drilling force is a good predictor of bone strength and quality.

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