12th Brazilian Congress of Manufacturing Engineering
May 10th-12th, 2023, Brasilia, DF, Brazil

BONE PROPERTIES - A REVIEW FOR DRILLING APPLICATION

Raafat Hussein
Yann Landon
Anna Carla Araujo
Institut Clément Ader, Université de Toulouse, CNRS/INSA/ISAE/Mines Albi/UPS, France
raafat.hussein@univ-tlse3.fr
yann.landon@univ-tlse3.fr
araujo@insa-toulouse.fr

Abstract. *Bone is the main organ of the skeletal system, composed of cells, collagenous fibers, non-collagenous proteins and minerals. The mechanical properties of bone maintain the shape of the body and transmit muscle contraction forces during movement. It is a dynamic, anisotropic, hierarchical, heterogeneous and time-dependent biological material. Its properties vary more than those of typical engineering materials due to various factors such as bone function, age, weight, and other characteristics. Bone has been shown to have high mechanical compressive properties as a highly calcified hard tissue. However, temperature and other factors affect the compressive strength and fracture morphology. Despite the high load-bearing capacity of bone due to its structurally optimized tissue, severe impact or trauma can weaken bone and cause fractures. Some types of fractures require internal fixation through surgical bone drilling. Orthopedic surgery exposes bones to higher stress and temperature, resulting in permanent or temporary damage. This can lead to certain healing complications and mechanical instability. Many researchers have investigated numerous factors to reduce heat generation and prevent osteonecrosis. These include processing parameters, drill specifications, and bone properties. However, it remains a problem to more accurately determine the behavior of the bone and the corresponding actual drilling conditions, as these factors and their effects are closely related. To accurately predict the temperature rise during bone drilling using experimental and computational models, it is necessary to understand the geometry, mechanical behavior, and thermal properties of the bone tissue. Therefore, it is important to analyze the bone as a thermo-mechanical element to predict its behavior. This article reviews the basic concepts of bone biomechanics, its complex hierarchical structure, and its mechanical and thermal properties at the macroscopic and microscopic levels. It also highlights the factors that influence the large variability in the mechanical behavior of bone, as well as the studies on the thermomechanical conditions of bone drilling. Many recent experimental and theoretical studies have investigated the influence of drilling techniques on the mechanical and thermal responses during bone drilling. Regardless of the used technique, there is a wide range of variation in the mechanical and thermal response of bone. This is constantly related to structural factors and is dependent on the direction of loading. This comprehensive review can help surgeons and drill manufacturers understand recent improvements through optimal strategies to reduce or limit thermal damage during bone drilling.*

Keywords: *Biomechanics; Bone properties; Cortical structure; Implants; Bone machining.*

1. INTRODUCTION

Bone is a living tissue composed of cells embedded in an abundant hard intercellular material that makes up the skeleton of the body (Clarke, 2008). It has been the focus of interest of many researchers in the field of mechanics to understand and solve the problem of fractures related to the impairment of mechanical behavior by certain factors such as age and specific pathologies. Bone has the ability to renew itself after damage because its natural structural material repairs itself (Cowin (2001)). It is composed primarily of three cell types: osteoblasts, which are responsible for new bone formation, osteocytes, which are probably the sensors of mechanical stress and contribute to the degradation of the bone matrix, and osteoclasts which are multinucleated cells of the macrophage family that form from blood monocytes and responsible for aged bone resorption (Clarke (2008)). However, certain diseases and trauma damage the skeletal system, requiring clinical intervention in which bone drilling is involved for proper healing (Kim *et al.* (2020)).

Bone drilling is a surgical method used in orthopedics, mainly for repairing internal fractures, inserting implants, or reconstructive procedures. In this surgical procedure, holes are drilled into the bone and the fracture is fixed with screws or wires to immobilize it (Bohra *et al.*, 2019). It is an essential and universally demanding surgical procedure that generates both mechanical and thermal loading on the bone structure, resulting in an increase in bone temperature and stress. However, certain complications occur when drilling bone, such as uncontrolled plunging of the drill tip, mechanical instability, drill-bit breakage, lack of vascularization, in addition to bone loss and defects. The pivotal concerns of bone drilling are the time at which the temperature exceeds the threshold and the duration at constant temperature, which are detrimental to bone viability and can lead to osteonecrosis. According to the literature, the main sources of heat are plastic deformation of the produced chips and friction between bone and cutting surfaces of the drill (Shihao *et al.* (2021)). In addition, many processing parameters and drill specifications contribute to the temperature rise and drilling efficiency. The bone itself is also a source of heat generation due to its complex hierarchical structure and low thermal conductivity. Therefore, a successful bone drilling procedure requires adequate treatment of the mechanical and thermal aspects of bone.

In order to model drilling bones, it is important to understand the behavior of cortical bones submitted to a situation similar to orthogonal cutting model Baro and Deoghare (2018). The cutting parameters and cutting conditions play an important role in the temperature and the effect on the bones cells. Researchers have studied orthogonal cutting of bone to determine the cutting forces, chip geometry, surface quality and temperature. Despite the anisotropic nature of bone, Alam *et al.* (2009) developed a 2D isotropic finite element model for a bovine femur considering approximated as a fibre-reinforced composite to simulate its structure. Sugita *et al.* (2009) and Sugita and Mitsuishi (2009) also incorporated a one-dimensional continuous fiber reinforcement to analyse the bone using experimental approach and FEM on orthogonal cutting and analysing crack propagation and osteons alignment with cutting direction. Linear regression analysis was performed and a relationship between cutting force and crack length was suggested. Santiuste *et al.* (2014) included the effects of anisotropy on cutting forces and temperature also modeling cortical bone as a long fiber-reinforced composite material. In another study, Childs and Arola (2011) used finite element models of bone adapting metal cutting theory and a pressure dependent yield stress and a strain path dependent failure strain law and define the appropriate method for the bone cutting. Moreover, finite element models were used also by Baro and Deoghare (2018) to analyze the effect of orthogonal cutting parameters on three different models of cortical bone i.e., isotropic, anisotropic, and microscale models. They tested the effect of depth of cut, friction coefficient, cutting speed and rake angle on temperature and force levels. In microscale, Hage and Hamade (2013) applied FEM using a data-driven approach using microscope images enhanced by Artificial Intelligence of orthopedic cutting in cortical bone containing only osteons and interstitial lamellae.

Experimental analysis of orthogonal cutting is analysed in some articles. Sui *et al.* (2013) analyzed the significance of the parameters using experimental full factorial design of the cutting process when using stainless steel tools on bovine femur bones. ANOVA and regression analyses were used to determine the factors that have high and low significant influence. Recently, Zawadzki *et al.* (2022) analyzed experimental chip formation measuring cutting forces and evaluating the effects of the rake angle, clearance angle, and depth of cut on the orthogonal cutting process of cortical bone in three directions. In addition, Luo *et al.* (2022) used experimental analysis along with analytical models on cortical bone to analyze chip formations, material removal behavior and cracks propagation and initialization under varying bone osteon cutting angles and depths. Besides, Bai *et al.* (2020) also performed experimental analysis to study the mechanisms of material removal and crack propagation in orthogonal cutting of cortical bone but with the consideration of microstructural and sub-microstructural features and material anisotropy.

In recent years, research in the field of bone drilling has come into focus and so the orthogonal cutting model is applied to drilling operations. The main focus is on predicting and controlling forces and temperature to ensure the success of operations and reduce damage to bone tissue, such as osteonecrosis. Many experimental analyses were done with various drill tools to investigate bone drilling. For example, Wang *et al.* (2013) used manual and automated drilling in bovine cortical bone to study the drilling process, drilling forces and torque. They investigated separately the effects of drilling speed, feed rate and drill-bit diameter on forces and torque. Chen *et al.* (2021) used novel rotary heat pipe drill, a different drill tool to investigate the thermal management and heat transfer mechanism at different heat fluxes and spindle speeds. Low-frequency vibration-assisted drilling was used by Han *et al.* (2022) to determine the effects of machining parameters such as feed rate, rotational speed, vibration frequency, and amplitude on drilling temperature rise and chip morphology. Moreover, conventional drilling was performed on Sawbones and bovine bone by Samarasinghe *et al.* (2019) to comprehensively explore the effects of the processing parameters on drilling forces, temperature, osteonecrosis exposure and debris formation.

Shihao *et al.* (2021) implemented the drilling process on fresh bovine femur along wih for a comprehensive study of the thermal characterization of bones. Quasi-three-dimensional time-series temperature distributions were established and analyzed to formulate strategies to reduce thermal damage to bone. Other researchers conducted their investigations using non-conventional drilling. For example, Agarwal *et al.* (2022b) conducted histopathological studies on porcine femur bone using rotary ultrasonic bone drilling technique. They studied cutting forces, temperature, microcracks and bone chips generated during drilling and compared the results with a conventional twisted drill-bit of the same diameter. They also intended to develop several machine learning algorithms to predict temperature increases during rotating ultrasonic bone drilling (Agarwal *et al.* (2022a)).

In addition, numerical modelling and simulations were implemented for the study of drilling process. Liu *et al.* (2022) proposed a mechanistic model to predict thrust force and torque for a novel crescent-shaped drill with an improved positive rake angle. In the study by Wang *et al.* (2022), ABAQUS software was used to simulate the drilling of bone in a time-varying temperature field considering the aging factor. Additionally, the temperature of drilled bones was studied by Khan (2014) using a three-dimensional thermomechanical finite element model of bone drilling to determine the appropriate drilling parameters (cutting speed, feed rate) and cooling conditions. The latter was also investigated by Alam *et al.* (2015), where they performed a series of experiments and numerical studies to investigate the effects of cooling conditions on the increase in bone temperature during drilling.

Numerous investigations and research projects have been conducted to comprehensively evaluate the parameters in surgical bone drilling to mitigate thermomechanical damage to drilled bone. However, due to the complexity of parametric interactions, the problem of determining the ultimate ideal bone drilling parameters remains. This systematic review aims to understand the mechanical and thermal behavior of bone to achieve better surgical outcomes and reduce bone failure. It aims to provide an overview of the fundamental concepts of bone biomechanics and the mechanical tests that have been performed to characterize the multiscale mechanical behavior of bone. It also highlights various factors responsible for the wide variability in the mechanical and thermal properties of bone. In addition, the thermal characterization of bone in relation to specific factors will be examined. The relationships between the mechanical behavior of bone at different scales will allow a better understanding of the effects of changes in mechanical and thermal properties from one scale to another on damage and failure in drilling applications.

2. BONE STRUCTURE

The structure and fracture strength of the bone itself should be considered to determine the mechanical behavior of the bone during drilling, i.e., whether the bone will fail under mechanical or thermal loading. The mechanical complexity of bone exceeds that of all other engineering composites because bone has a hierarchically organized structure. This means that it has an irregular but optimized arrangement and orientation of fibers. Because of its hierarchical structure, bone has defined properties at each structural level, making the material heterogeneous and anisotropic. Figure 1 shows the five levels of hierarchical structural organization.

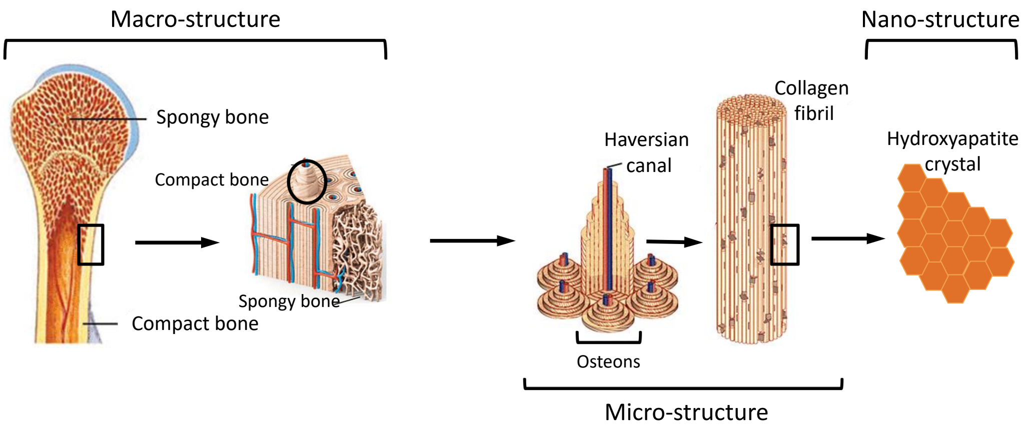

Figure 1: The five hierarchical structural levels in cortical bone: from the macroscale of cortical and cancellous bones to the nanoscale of collagen molecules - Adapted from Liu *et al.* (2016)

As it is presented in Fig. 1, the macrostructure level takes place from 10mm to several cm. At this scale, bone can be divided into two parts: Cortical bone, the dense bone that makes up 80% of the volume of the entire skeleton, and trabecular or cancellous bone, which makes up the other 20%. The main difference between these two types of bone tissue is porosity. Cortical bone has a porosity of 5% to 15%, while trabecular bone has a porosity of 40% to 95% (Morgan *et al.* (2018)). Adult long bones consist of two broad and rounded epiphyses on either side of a central cylindrical shaft. Cortical bone forms the diaphysis, while cancellous bone with a thin shell of cortical bone forms the epiphysis and metaphysis (Cowin (2001)). Cortical and trabecular bones also differ in their mechanical properties. The mechanical behavior of cortical bone is anisotropic. However, due to the small differences in mechanical properties in both radial and circumferential directions, it is considered a transversely isotropic material. The trabecular bone or spongy bone of the typical size of $5-10mm$, in which the trabeculae and the intervening pores can be observed simultaneously, is considered a highly porous anisotropic material (Morgan *et al.* (2018)). This porosity mainly determines the mechanical properties of trabecular bone. The structural arrangement of the trabecular network and the tissue-level properties of a trabeculae also contribute to the apparent mechanical behavior. Moreover, the macroscopic mechanical properties of bone vary between regions of the same type of bone tissue (Ovidiu *et al.* (2014)).

The mesostructure level which is on a scale of $0.5-10$ mm where the osteons are randomly arranged within the interstitial lamellae with cavities for absorption. Furthermore, the microstructure level is on a scale of $10-500$ μm. At this level, the cortical bone can be seen as a Haversian system composed of a long narrow cylinder called the osteon consisting of concentric layers of lamellae that surrounds the Haversian canal. The mechanical properties of osteons vary with collagen fiber orientations, mineral density, and loading modes (Atthapreyangkul *et al.* (2022)).

At the nanostructure level, the bone matrix can be described as a composite of collagen fibrils and mineral plateletes having an hexagonal lattice structure of hydroxyapatite (Ma *et al.* (2020a)). Recently, researchers are focusing on the micro-mechanical properties of cortical tissue isolated using conventional machining technologies with length scales below a few hundred micrometers.

3. MECHANICAL CHARACTERISATION OF BONE MATERIAL

The classical mechanics principles and solid mechanics are used to study the material fracture toughness when subjected to a certain load. Bone, the bio mechanical organ of the skeleton system, has always been a subject of great interest in mechanics. The analysis of bone biomechanics is vital to determine the mechanical properties of bone to detect failure and damage aspects during process.

Most of the studies in the literature have been performed on the cortical bone because of the importance of the multiscale structural function. Recently, researchers are moving toward analyzing and modeling the mechanobiology of trabecular bone since it is the main load-bearing bone in vertebral bodies and also it transfers the load from joints to the compact bone of the cortex of long bones (Audekercke and Martens (2018), Giesen *et al.* (2002), Michimoto *et al.* (2020)).

Due to bone's hierarchical structure and complexity, scale is of great importance when discussing bone architecture and properties. Every mechanical test has its own resolution for assessing the properties of a given structure (Rho *et al.* (1998)). Therefore, it is crucial to combine certain mechanical techniques to determine the properties of bone at its different scales using standard tests for mechanical characterization.

3.1 Mechanical properties of bones using macroscale tests

At the macroscale, the most common mechanical methods performed are the tensile, compression, bending and torsional (Albert *et al.* (2021), Atthapreyangkul *et al.* (2021), Reilly and Burstein (1975a)). These methods are usually used to reveal bone stiffness represented by the elastic modulus (E), shear modulus (G), Poisson's ratio (ν), bone ultimate strength (σ) and failure resistance.

The mechanical behavior of bone at the macroscale varies according to the type of bone, whether it is cortical or cancellous, and according to the anatomical function in the skeletal system. For example, femur is one of the longest and strongest bones in the body and is essential for standing and movement (Reynolds (2013)). Under various loading modes, the ultimate strength of human femoral cortical bone is greatest under compression in the longitudinal direction ($135 \pm 15.6\, MPa$) and weakest under tensile loading in the transverse direction ($53 \pm 10.7\, MPa$) performed on 1cm human femoral cortical bone (Reilly and Burstein (1975b), Mirzaali *et al.* (2015)). As cortical bone is loaded longitudinally, it is characterized by a bilinear stress-strain response that distinguishes linearly elastic and linearly hardening regions at a given yield point, fracturing abruptly at less than 3% fracture strain. Ascenzi *et al.* (1994) calculated stiffness using shear experiments resulting $4GPa$ and by traction (tension and compression) as $5-12GPa$. A pull-out and push-out test also revealed that the cement line has a lower interfacial strength than the osteonal lamellae.

A summary of the values reported in some studies for the elastic mechanical properties for long bones assessed at the macro scale is presented in Tab. 1. According to the literature , the average Young's modulus of human long cortical bones under tension is approximated between the range of 17 *GPa* and 24 *GPa* in the longitudinal direction, and between 11.5 *GPa* and 15.2 *GPa* in the radial direction. In addition, it was reported that bovine bone properties are close to human properties, where its elastic properties vary between 21.9 *GPa* and 30.3 *GPa* in the longitudinal direction, and between 11.6 *GPa* and 17.3 *GPa* in the radial direction (Morgan *et al.*, 2018).

The trabecular tissue, as well, is considered to be linearly elastic material and the yield point is defined by a 0.2% offset method (Birnbaum *et al.* (2001)). The density of trabecular bone can be measured using several different methods. The ratio of mineralized tissue content to volume of bone of interest is defined as bone volumetric mineral density (vBMD). Alternatively, volume fraction can be defined as the ratio of the volume of mineralized tissue to the volume of the sample, or, equivalently, as one minus porosity. The vBMD of human trabecular bone ranges from $0.058-0.263g/cm^3$, whereas the vBMD of human cortical bone ranges from $0.406-1.018g/cm^3$. The variations in density depend on the anatomical region of the bone and the measurement and calculation technique used (Liu *et al.*, 2010). In the primary compression group of the femoral neck, the trabecular bone accounts for 60% of the total volume (Morgan and Keaveny, 2001). Trabecular bone can exhibit considerable spatial diversity in terms of density and structure, which in turn can result in wide variability in apparent elastic modulus and strength properties. The human trabecular modulus of elasticity ranges broadly from 10 to $3,000$ MPa, while strength, which is linearly correlated with modulus of elasticity, ranges from 0.1 to 30 MPa (Morgan and Keaveny (2001)). Like cortical bone, trabecular bone exhibits the highest value in compression rather than in tension, but has the lowest value in shear (Yeni *et al.* (2004)).

There are few studies in the literature on the dynamic response of bone at the macro level, though bone is a time-dependent biological material. Some studies reported stress, strain and strain-rate analyses at different test velocities

(McElhaney (1966)). McElhaney (1966) showed, using an air-gun testing machine, that the mechanical properties of bone in compression depend on the rate of deformation and the critical velocity is detected at a strain rate of $1s^{-1}$. This method is used to apply constant compression loads with a strain rate up to $4000s^{-1}$. An increasing in the elastic modulus from 15.1GPa to 29.5GPa was reported with the increase in strain rate from $0.001s^{-1}$ to $300s^{-1}$. Another method to measure the dynamic mechanical properties of the femoral cortical bone is using Hopkinson bar stress technique by which the measured Young's modulus (19.9 *GPa*) in dynamic conditions ($\dot{\varepsilon} = 100s^{-1}$) is 23% higher than the average Young's modulus (16.2 *GPa*) in static conditions (Katsamanis and Raftopoulos (1990)). Also, Halldin *et al.* (2014) measured the behavior of anisotropic cortical bone in tension at a range of strain rate between $0.01s^{-1}$ and $200s^{-1}$, where they found that at a strain rate of $0.1s^{-1}$, bone has the maximum energy absorption capability.

Another reported dynamic method is based on ultrasound technique, a non destructive test and preserves the bone structure. It is performed with different ultrasound modes by varying the wave frequency (from kHz to MHz) and the propagation media. One of its main advantages is that the mechanical test can be performed in different directions within the same bone sample (Bensamoun *et al.* (2004)). This technique is performed either by the reflection technique or by the transmission technique, where in the latter the ultrasound beam propagates through the bone interior and analyzes the entire bone volume, whereas in the reflection technique the bone surface is studied only (Antich *et al.* (2009)). Therefore, the mass and structural density of the bone specimen affect the transmission technique rather than the reflection.

Reference	Bone specie	Anatomical region	Test	Loading direction	Elastic Modulus (GPa)
Reilly and Burstein (1975a)	Human	Femur	Compression/ tension	Longitudinal/ radial/ transversal	$E_{long} = 17$ $E_{rad} = 11.5$ $E_{trans} = 11.5$
Bayraktar *et al.* (2004)	Human	Rib	Compression	Longitudinal	$E_{long} = 12.51$
Bayraktar *et al.* (2004)	Human	Femur	Compression	Longitudinal	$E_{long} = 17.04$
Mirzaali *et al.* (2015)	Human	Femur	Tension/ compression/ torsion	Longitudinal	$E_{tens} = 18.16 \pm 1.88$ $E_{comp} = 18.97 \pm 1.84$ $G_{tors} = 6.07 \pm 0.57$
Lipson and Katz (1984)	Bovine	Femur	Ultrasound	Longitudinal/ radial	$E_{long} = 24.7 \pm 1.0$ $E_{rad} = 16.7 \pm 0.5$
Wang *et al.* (2007)	Bovine	Femur	Compression	Longitudinal	$E_{long} = 12.5 \pm 1.9$

Table 1: Some literature review about bone mechanical properties assessed by several mechanical tests and ultrasound

3.2 Mechanical properties of bones using micro and nanoscale tests

At the microstructure level, nanoindentation, micro/nanoscratch tests and micromechanical tests were processed on micropillars with a focused ion beam or femtosecond laser to explore the micro properties of the bone tissue. Nanoindentation is the most frequently used technique to characterize the local micromechanical properties, computed by the elastic-plastic Oliver-Pharr mechanical method Ma *et al.* (2020a). The elastic moduli of human femoral osteonal and interstitial lamellae measured by nanoindentation, under dry conditions in longitudinal direction, are between the ranges of $16.1 - 25.8$ *GPa* and $15.1 - 26.1$ *GPa* respectively, and are about 45% lower in the transverse direction (Franzoso and Zysset (2009), Bayraktar *et al.* (2004)). The hardness was also detected to be between 0.30 and 0.65 *GPa* for the osteonal zone and between 0.51 and 0.8 *GPa* for the lamelar bone.

However, compression tests on micropillars show that both strength and ductility of cortical tissue are higher at the microscale than at the macroscale (Diab and Vashishth (2007)). Casari *et al.* (2021) reported that the cortical bone strength at the lamellar level is affected by the orientation of the osteonal fibers of about $\pm 30°$, and the specimens showed highly anisotropic response compared to the macroscale under microtensile loading. Preliminary microscale fracture toughness values are comparable to those measured at the macroscale. The mechanical properties of cortical bone focused largely on porosity and mineralization. Cortical porosity is negatively correlated with elastic modulus, ultimate compressive stress, and fracture toughness (Roy *et al.* (1999)). Changes in porosity account for more than 75% of the variation in cortical bone strength. At the microstructural level of trabecular bone, the anisotropy is also found in the elastic modulus and

Reference	Bone specie	Anatomical region	Test	Elastic modulus (GPa)	Hardness (GPa)
Roy *et al.* (1999)	Human	vertebrae	Nanoindentation (Oliver- Pharr model)	$E_{long} = 18.1 \pm 2.7$ $E_{trans} = 16.9 \pm 3.2$	$H_{long} = 0.549 \pm 0.07$ $H_{trans} = 0.542 \pm 0.1$
Bayraktar *et al.* (2004)	Bovine	Femur (osteons)	Nanoindentation	$E_{long} = 24.7 \pm 2.5$ $E_{trans} = 19.8 \pm 1.6$	0.647 to 0.892 transversal direction
Bayraktar *et al.* (2004)	Bovine	Femur (interstitial lamellae)	Nanoindentation	$E_{long} = 30.1 \pm 2.4$ $E_{trans} = 19.8 \pm 1.6$	0.647 to 0.892 transversal direction
Bensamoun *et al.* (2008)	Human	Femur	Nanoindentation (Oliver- Pharr model)	$E_{long} = 21.3 \pm 3.0$	$H_{long} == 0.55 \pm 0.15$ Dry conditions
Rodriguez-Florez *et al.* (2012)	Mice	Femur	Nanoindentation (VEP model)	$E_{dry} = 33.7 \pm 6.4$ $E_{wet} = 27.5 \pm 6.5$	$H_{dry} = 0.75 \pm 0.16$ $H_{wet} = 0.26 \pm 0.04$ Longitudinal direction
Meng *et al.* (2021)	Bovine	Tibia	Nanoindentation (Creep model)	$E_{reduced} = 19.75 \pm 1.16$	$H = 0.883 \pm 0.051$ Fatigue loading in 4-point bending
Casari *et al.* (2021)	Ovine	Tibia	Microtensile quasi-static testing	$E_{long} = 27.7 \pm 3.4$ $E_{trans} = 13.6 \pm 1.1$	N/A

Table 2: Examples of bone mechanical properties from literature assessed by nanoindentation and microtensile tests

strength Odgaard *et al.* (1997)). However, the fracture toughness of trabecular bone has not been well studied because the porous and spatially heterogeneous microstructure don't meet the requirements for a fracture toughness test. Nevertheless, the cyclic compressive loading of trabecular bone, even at low loading rates, leads to the loss in stiffness and strength, in addition to the accumulation of residual strain (Cook and Zioupos (2006)).

Concerning the viscoelastic response to detect the time-dependant properties of bone at the micro level, Oliver-Pharr mechanical method exhibited significant miscalculations. Therefore, researchers tended to use other methods to consider the effects of strain rate on the mechanical response of bone. The visco-elastic-plastic (VEP) model and creep analysis were used to reveal the viscoelastic properties of bone at the microscale. In the former model, three extensive quadratic elements (viscous, elastic, and plastic) are used in series to create a time-dependent indentation model. In creep analysis, the usual method is to apply a constant load to the indenter and then measure the depth produced as a function of time. With fracture, the creep viscosity of the bovine tibia decreased from 5442 GPa to 4886 GPa, while the time constant increased from 1.42 s to 1.46 s Meng *et al.* (2021). According to the data reported in Tab. 2, the mechanical response of bone depends on the loading direction, and the variations in the mechanical properties are due to the hydration state and the indentation zone (whether within the osteons or the interstitial lamellae). However, unlike the macro mechanical properties, small variations were found between cortical and cancellous bone at the microscale and this is due to the decrease in local porosity Ovidiu *et al.* (2014).

3.3 Factors affecting bone properties

Evaluating the mechanical properties of bone remains a challenge because bone qualities vary widely from species to species, depending on bone mass, mass distribution and material properties in addition to age, gender and diseases. The determined mechanical properties of bone vary according to different loading conditions, including loading types, loading rates, and boundary conditions. These results are inconsistent due to various intrinsic and extrinsic factors.

3.3.1 Intrinsic factors

The mechanical properties of bone depend on the total mass of the specimen, the geometric distribution of the mass and the material properties. Therefore, bone tissue can be strengthened by increasing the total mass or distributing the mass of the bone to locations where subjected to loads or by improving the material properties of the constituent tissue. As an example, some animal models have reduced material properties of their bone tissue compared to others, but its defined structural geometry makes the structural properties comparable and with reduced risk of fracture (Awede *et al.* (1999), Bonadio *et al.* (1993)). Cortical bone mass can be measured directly from the cross-sectional area, whereas cancellous bone is more complex and since it is spatially varying, its mass is measured in small homogeneous volumes of tissue at micro or nano level. Bone mass is usually measured as bone mineral content and it is determined through several in-vivo imaging technique such as QCT (Luo (2017)). It is quantified including the bulk porosity for the cancellous bone by the apparent density, the mass of the bone tissue present in the total volume of the specimen. It can explain the 60% to 85% of the variability in the compression apparent stiffness measured experimentally (Morgan *et al.* (2003), Luo (2017)). According to literature, small variations in the bone mass have large variations in bone strength and elastic modulus due to the squared power law strength-density relationship and power law modulus-density relationship with exponent between 2 and 3 respectively (Morgan *et al.* (2003), B and Huiskes (2001), Moshage *et al.* (2022)).

However, measures of the bone mass take only the total bone tissue quantity and doesn't reflect the localisation of this tissue. Hence, as for engineering composite materials, same density materials may differ in their mechanical properties due to different parameters and structures at the micro level, e.g. the orientation of fibers, the amount non-collagenous and collagenous proteins, the density gradient of the Haversian canals and geometric parameters. The cross-sectional area, moments of inertia, and cross-sectional modulus are the geometric parameters that asses the geometric distribution of the bone material and modify its mechanical behavior under different types of loading.

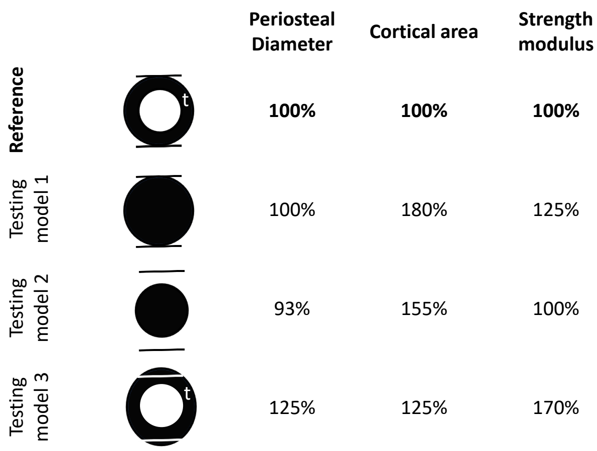

Figure 2: The effect of the geometric distribution of the bone mass on the section modulus and the whole bone strength - Adapted from van der Meulen *et al.* (2001)

In particular, for bending and torsional loads, the strength of the material is higher when the tissue is further away from the bending plane or the torsional axis. Assuming that the structures in Fig. 2 consist of the same material, the section modulus increases exponentially with external diameter since the periosteal surface of the solid cylinder resist the bending load more than the central core (van der Meulen *et al.* (2001)). A solid cylinder (test model 1) with the same periosteal diameter as the hollow cylinder (reference model) has 80% greater surface area, but only 25% greater bending strength. However, a solid cylinder of test model 2, which has only 7% less periosteal diameter compared to the reference model, has equivalent section modulus and thus equivalent strength. In contrast, the flexural strength of test model 3, a hollow cylinder, is 70% higher than that of the reference model when the bone mass is increased by 25% to the periosteal diameter. In cancellous bone, the homogeneous micro-volume taken from the sample showed that the sites with the same mineral density but different architectures and geometric distribution exhibited differences in strength and stiffness up to 50% (Birnbaum *et al.* (2001)). In addition, cancellous bone often shows different mechanical behavior when loading with different direction. For instance, in human vertebrae, the alignment of the trabeculae along the axis of the spine makes the bone specimen, when loaded along superior-inferior axis, two times stronger than when loaded along the anterior-posterior or right-left direction. Another determinant of the bone mechanical properties is the properties of the constituent material.

Naturally, cortical and cancellous bone consist of laminar tissue but with different microstructure organizations. The extracellular matrix of the bone primarly constitutes of an organic phase of collagen type I protein which can undergo various molecular level biochemical modifications such as intra- or inter-molecular cross-linking of enzymatic pathway. The impaired formation of enzymatic cross-links contributes directly to the decrease in bone strength and to the postyield deformation of the tissue (Vashishth *et al.* (2001), Robins and Bailey (1972)). Bone tissue also constitutes of an inorganic phase of crystalline mineral where it contributes directly to the material stiffness at the nano level and therefore to the whole bone stiffness at the macro level (Hasegawa *et al.* (1994), Tsou (2003)). Although the mineral content is not preserved where it is affected by the age, the cyclic loading due to daily activities and the temperature (Sroga and Vashishth (2012), Ma *et al.* (2020b), Bumrerraj and Katz (2002)). Microdamage induced by fatigue may be more likely to cause fractures near cortical pores than in areas of high mineral content. However, increased mineral content, as may occur with long-term therapy with bisphosphonates for the treatment of osteoporosis, is associated with reduced fracture strength (Lloyd *et al.* (2017)).

3.3.2 Extrinsic factors

There are also external factors that contribute to the wide variability in bone mechanical properties. One of the time-dependent factor is the age of the living organisms. In addition to that, certain pathologies, gender and temperature alter the mechanical behavior of bone. Understanding these factors and their effects on the bone strength and stiffness from the nano level to the micro level is merely the first step to minimize fracture risk due to drilling applications. Material strengths and stiffness of bone decrease with age in both women and men. From the third decade of life, the strength of cortical bone in tension and compression decreases by about 2% per decade, while fracture toughness decreases by about 4% (Sroga and Vashishth (2012)). In addition, under impact loading, the energy required to fracture a cortical bone specimen decreases by threefold from age 3 to 90 years (Panagiotopoulos *et al.* (2005)). These deteriorated mechanical properties are due to the increased probability of being infected by osteoporosis, the increase in porosity and the susceptibility to fractures with aging (McCalden *et al.* (1993), Ross *et al.* (1991)).

Moreover, human trabecular bone also reveals a decrease in material properties with aging, as a result of a drop in the apparent density values. The ash density of the vertebral trabecula decreases by about 50% from the age of 20 to 80 years and also the compressive modulus, ultimate stress, and energy to failure decrease approximately 75% to 90% (Tsou (2003)). Not only does the density of bone tissue decrease with age, but also the microstructure undergoes modifications. For example, the osteonal density increases with age, as an indication of the presence of more small osteons in specific tissue area and therefore the density of the osteon cement lines increases. Hence, this density gradient affects the initiation of the microcrack and expands the direction of the fracture surface (Ma *et al.* (2020b), Diab and Vashishth (2007)). Therefore, the trabecular bone is weaker with age due to the perforation of the trabecular plates resulting in less connected thinner rod-like trabeculae. Although aging is an external factor, it is attributed to the constituent of the tissue such as the amount of collageneous and non-collagenous proteins. For example, the accumulation of AGEs changes microdamage production and morphology resulting in producing more fragile bones in olders. In addition, the orientation and spatial distribution of the collagenous fibers affect bone toughness. Furthermore, the non-collagenous proteins content are altered through age where up to fourfold non-collagenous quantity is found in younger bone tissue compared to older one (Ascenzi *et al.* (2015), van der Meulen *et al.* (2001)).

However, the loss and fragility in bone tissue with aging differ between genders. In woman, the volume fraction is decreased due to the trabecular loss, whereas in men, the decreased of volume fraction is referred to trabecular thinning. A study shows that for trabecular thinning (in men), a 10% drop in bone density results in 20% bone strength reduction. On the other hand, for trabecular loss (in women), bone strength is decreased by 70%, and 77% for both trabecular thinning and loss under the same percent of bone density reduction (Stauber and Müller (2006)). Hence, the mechanism of loss bone in women is more detrimental to the mechanical behavior even if the loss amount is restored by trabecular thickening. It is found in the literature that the cortical thickness of long bone is the same for both women and men with aging, though, men have greater section modulus due to the greater periosteal expansion resulting in more resistance to the applied loads. Therefore, women long bones are more susceptible to fracture due to the inability to compensate the periosteal apposition. Researchers have examined the microstructural changes in the cortical and trabecular compartments of the peripheral skeleton using high-resolution CT imaging. In men, the cortical area is nearly the same and the moment of inertia increases as they age. Whereas in women both of them decrease and thus osteoporosis puts them at the risk of fractures as they age (Gold *et al.* (2022)).

In addition, many diseases affect the structure and material properties of bone tissue and therefore, they are detrimental to the mechanical behavior of the whole bone. According to the French Society of Rheumatology (SFR), around 145000 suffer from bone fracture due to diseases. Osteoporosis, for example, is a pathological state where bone density dropped below the average density of its age, which leads to the more fragile and weak bones as it increases the risk to break Morgan *et al.* (2018). This disease leads also to change in the material constituent. During remodeling period with rapid alterations in bone density, mineralization is shifted towards hypomineralization (lower densities). For cancellous bone, several tests were performed at every level of bone hierarchical structure to determine diseases-related changes in mechanical properties and it was found that the trabecular number and the volume fraction deteriorated.

4. TERMOMECHANICAL CONDITIONS IN BONE DRILLING

Besides the mechanical properties, it is also difficult to asses the thermal properties of bone due to its wide quality variability. The thermal effect of bone drilling leads to an increase in temperature. This effect is crucial for bone injury, as it can lead to necrosis or irreversible loss of bone cells, resulting in infection and reduced mechanical strength. Bone drilling behavior is determined by several factors, including the cutting tools used, the machining conditions (feed rate and spindle speed), and the mechanical and thermal properties of bones. Drilling performance is evaluated by cutting forces (thrust and torque) and the resulting temperatures.

4.1 Bone thermal conditions in drilling

Bone exposed strong compressive resistances, but it is strongly affected by the loading direction and the fibrils' orientation. The compressive properties of cortical bone are also temperature dependent. Ma *et al.* (2020b) shows that the compressive properties of fresh tibial porcine cortical bone immersed in a 38 $°C$ thermostat exhibit relatively low strength compared to specimens presented at room temperature. Strength attenuation is associated with temperature sensitivity of organic matter strength within cortical bone. Therefore, surgical bone drilling that generates high thermal and mechanical loads changes bone properties, and thus compromises bone healing and implant reliability. Applied cutting forces induce plastic deformation within the workpiece material, resulting in shear deformation and chip formation along the shear plane. A part of this mechanical work is converted in thermal work. The high heat generated during surgical drilling, resulting in excessively high tissue temperatures, can lead to thermal osteonecrosis, the phenomenon of bone death. Oblique drilling, processing parameters, drill geometry, and bone properties are factors that affect the maximum temperature, duration of overheating, and the thrust force.

Most of the drilling procedures discussed in the literature were examined at room temperature and under dry conditions. Bone drilling experiments, with different conditions, were performed on bone species to study the properties of the bone during the drilling process to avoid bone damage and failure. They investigated the relationship between drill-bit sizes, drill speed, bone stiffness, and triaxial compressive strength. The authors found that drill strength was directly correlated and proportional to bone triaxial compressive strength (Karalis T (1982)). However, no linear correlations were found between hardness and drill strength. Robles Linares Alvelais *et al.* (2021) found different damage degrees induced by drilling in vitro bovine cortical bone. They performed micro-pillar compression tests to identify changes in properties and failure modes caused by drilling, and found that lower bone modulus (42%) and strength (41%) were revealed near the machined surface, in addition to brittle behavior, at high temperature. On the contrary, no damage was revealed at the bulk bone and pristine properties with ductile behavior were detected. Additionally, histology evaluated necrosis, revealing that the weaker and brittle bone layer accounts for more than three times as much area as the necrotic layer.

Hillerya and Shuaibb (1999) studied the effects of temperature on the physical aspects of bone when drilling human and bovine bones. They found that temperature increased with increasing drilling depth. A higher temperature is observed when drilling bovine bone than human bone. This is because bovine bone has mean cortical thickness (7 to 9mm) greater than that of the human one (2 to 3mm), where increasing cortical thickness is positively correlated with increasing maximal mean temperature. Feldmann *et al.* (2018) conducted experimental studies to analyze the thermal conductivity of bovine cancellous bone and human cortical bone. Cortical samples were tested using a custom steady-state and a widely used transient experimental setup, and the results were compared. Measurements were performed using micro finite elements (μFE) and micro-computed tomography (μCT). The thermal conductivity of bovine cortical bone was found to be 0.64 ± 0.04 W/mK, while that of human cortical bone was 0.68 ± 0.01 W/mK.

Shihao *et al.* (2021) also established and analyzed a pseudo-3D maximum temperature distribution, a temperature history at different distances, and a time series distribution of temperature at different times. The temperature distribution did not exhibit anisotropy under the different directions, and maximum temperature and exposure duration showed differences in the three different directions (parallel, perpendicular and transverse) due to the different removal mechanisms. The maximum temperature and exposure duration, in the vicinity of the hole wall, are mainly affected by the drill lip-cutting and margin friction stages. In addition, in inclined drilling, the temperature distribution showed a strong directionality due to the asymmetric friction caused by lateral forces. While the exact temperature at which necrosis occurs is not yet detected, the temperature of 47°C for a duration of 60s is considered a consensus threshold temperature (Shihao *et al.* (2021), Samarasinghe *et al.* (2019), Eriksson *et al.* (1984)). However, Samarasinghe *et al.* (2019) showed that the threshold of 55$°C$ for 30 seconds had a higher probability of thermal necrosis than 47$°C$ for 60 seconds.

4.2 Cutting parameters for bone drilling

Numerous studies have focused on understanding the process behavior by examining the effects of spindle speed, feed rate, and applied forces on bone temperature. Samarasinghe *et al.* (2021) found that increasing spindle speed from 1000 rpm to 2500 rpm increases temperature, and within the same range of cutting speed, increasing feed rate from 30 mm/min to 60 mm/min decreases temperature, while Alam *et al.* (2015) found that the temperature increases with increasing both, the spindle speed (from 1000 rpm to 3000 rpm) and feed rate (from 30 mm/min to 70 mm/min at constant cutting speed of 2000 rpm). Yang *et al.* (2010) performed high-speed drilling on porcine bones to investigate the drilling temperature and axial force under different drilling parameters. The process variables were rotational speed, feed rate, and drill geometry. A newly developed drill-bit with a W-shape and three cutting tips at the drill tip was used. The results were compared with the SS drill commonly used in hospitals. It was found that feed rate and drilling speed have the greatest effect on the drilling force and temperature generated. The drilling speed varied with the drilling depth. The newly developed surgical drill-bit produced lower drilling force and temperature (less than 47°C) compared to SS and carbide drills.

Lee *et al.* (2012) performed drilling tests on bovine cortical bone and developed a mechanistic model to predict drilling torque and feed force. They performed a calibration test to investigate the variations of specific energies with cutting speed, feed rate, and radial position. It was found that torque increased at higher feed rates and higher rotational speeds due to chip evacuation force and friction between the drill rim and the hole. Karaca *et al.* (2011) conducted several experiments on male and female tibias to investigate the effect of sex, mineral density, drill speed and tool-tip angle, drilling forces, and feed on heat generation during orthopeadic drilling. It was found that the temperature increased directly with drilling speed, while it decreased at high feed rate and drilling forces. Drilling speed was found to be the most important process variable. They also found that temperature was higher in female bovine tibia than in male tibia. In addition, the effects of different drilling speeds on strain generation were studied (Fonseca *et al.* (2018)). They also studied the temperature distribution on the drill surface when drilling tibiae from human cadavers and femora from cattle. It was found that both bone strain and drill temperature were higher when drilling bovine femora compared to human tibial heads as drilling speeds increased.

Udiljak *et al.* (2007) investigated the possibilities of high-speed drilling to avoid thermal bone necrosis, and it was found that cutting speed has no effect on axial drilling force but a significant effect on increasing bone drilling temperature. On the contrary, the increase in feed rate per tooth increases the axial drilling force but reduces machining time and friction duration. Therefore high feed rate results in lower bone drilling temperature. They recommended minimum cutting speed value of 6 m/min and high drilling feed rate at 0.1 $mm/tooth$ for temperature reduction in classic drilling. Shihao *et al.* (2021) showed that the maximum temperature exhibited a declining trend with the feed rate but it increased with the increase in spindle rate. Whereas the exposure duration presented a declining trend with both the feed rate and the spindle speed. Similarly, Samarasinghe *et al.* (2019) showed an opposite behavior of spindle speed and feed rate on temperature and force. Higher spindle speeds increased temperature but minimized forces, while higher feed rates decreased temperature but maximized forces. They also investigated the effect of the processing parameters on chip formation where they found that bone chips changed from a continuous spiral to a powdery shape as the spindle speed increased. In addition, Eriksson *et al.* (1984) performed drilling experiments on canine, human, and rabbit femoral cortex to measure temperature by attaching a Richards plate to stabilize a pertrochanteric fracture with a twist drill ($\theta = 3mm$, tip angle $= 118°$, helix angle$= 30°$). The authors observed that at a drilling spindle speed of $20,000$ rpm, the measured temperatures in rabbits, canines, and humans, were $40°C$, $56°C$, and $89°C$, respectively. Heydari *et al.* (2018) performed drilling studies on bovine bone and analyzed the drilling temperature using analytical models. It is reported that the process temperature increases with increasing drilling speed. The temperature also increases at low feed rates due to the longer contact time between bone and tool, and at high feed rates due to the high forces and friction.

4.3 Drilling tool specifications

Drill geometry, such as point angle, helix angle, drill diameter and affect drilling performance and bone final temperature (Shihao *et al.* (2021)). The entire heat generated during drilling increases with the increase in drill-bit diameter and thus temperature increases (Lee *et al.* (2011),Augustin *et al.* (2008)). On the contrary, Shihao *et al.* (2021) found a non-monotonic relationship between the drill-bit diameter and the temperature elevation. Obviously, researchers showed conflicting observations on drill-bit diameter, temperature and thrust force Samarasinghe *et al.* (2021).

For a drill diameter of 2.5 mm, the lowest process temperature (35.6°C) was obtained when drilling at a spindle speed and feed rate of 500 rpm and 30 mm/min respectively. In addition, Shihao *et al.* (2021) performed drilling experiments on fresh bovine femurs with different drill-bit diameters (2.5mm, 3.2mm, 4.2mm) and found that the highest temperature elevation (82.3°C), achieved by the 3.2mm drill bit, was approximately 10 and 21°C higher than those of the 2.5 and 4.2mm drill bits, where the highest temperature achieved did not exceed 47°C. By increasing the drill-bit diameter, chips can be evacuated more efficiently and the drill bit's heat capacity increases, reducing heat transfer to the surrounding tissues. But in this study, a non-monotonic relationship between the temperature elevation and drill bit diameter was detected.

Natali *et al.* (1996) performed an experiment on fresh human tibial cadavers to study different commercially available drills ($\theta = 2.5mm$). Different drill-bits of same diameter (2.5 mm) were used, such as a used standard orthopaedic tool, a new standard orthopaedic drill tool, a standard orthopaedic bit with blocked flutes, a HSS tool (High speed steel) twist tool, and a HSS drill-bit with tip angles of 90 and 118°. The results showed that a split-point bit (tip angle=118°) of HSS caused the least thermal damage to nearby bone and also reduced the penetration force by half. Ultimately, the authors suggested using split-point drill-bit with a point angle of 118° and a quick helix with an additional parabolic flute to reduce the force required and therefore reduce thermal damage in orthopaedics. Similarly, Udiljak *et al.* (2007) studied the effect of drill geometry on temperature and axial drilling force. They found that the axial drilling force is strongly influenced by the drill tip angle but the values of drill tip angle do not affect the drilling temperature. The axial drilling force is minimized when the drill tip angle is kept to a minimum (80°). They also concluded that in conventional bone drilling, a two-phase drill would be the suitable option to avoid temperature rise in the bone.

5. CONCLUSION

Bone drilling is essential in orthopaedic surgery to repair broken bones and replace damaged bones. High mechanical stress and temperature during drilling affect postoperative recovery and healing. In this review, extensive research has been conducted to understand the mechanical and thermal properties of bone. First, the structure and functions of bone were explained in detail. This was followed by a summary of the methods and results for multiscale mechanical testing of the hierarchical structure of bone and the extrinsic and intrinsic factors that contribute to the wide variability in the mechanical properties of whole bone. The variability of the macro- and micromechanical properties of the bone is also due to the test conditions, such as the specimen restraint, the type of loading, the loading rate, and the boundary conditions. The complexity of the bone structure and its anisotropy give it a high load capacity and resistance to compression.However, certain traumas or severe impacts may result in bone fractures and surgical procedures. In surgical bone drilling, the mechanical properties of the bone change, and the excessive rise in temperature leads to osteonecrosis. The reasons for the temperature and force increase are due to the drill specifications, machining parameters, and bone properties, as well as the complex interaction of the drilling environment. For better prediction and control of heat in surgical bone drilling, all these factors should be further investigated so that a parametric model can be developed and thus bone damage and osteonecrosis can be avoided. This comprehensive analysis of mechanical and thermal behavior under certain drilling conditions would lead to additional contributions toward identifying favorable conditions that are optimal for certain surgical conditions and thus improve the chance of successful surgery.

6. REFERENCES

Agarwal, R., Singh, J. and Gupta, V., 2022a. "Prediction of temperature elevation in rotary ultrasonic bone drilling using machine learning models: An in-vitro experimental study". *Medical Engineering Physics*, p. 103869. doi: 10.1016/j.medengphy.2022.103869.

Agarwal, R., Singh, R., Gupta, V. and Singh, J., 2022b. "Influence of cutting force on temperature, microcracks and chip morphology during rotary ultrasonic bone drilling: An in-vitro study". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 44. doi:10.1007/s40430-022-03608-6.

Alam, K., Khan, M., Muhammad, R., Qamar, S.Z. and Silberschmidt, V.V., 2015. "In-vitro experimental analysis and numerical study of temperature in bone drilling". *Technology and Health Care*, Vol. 23, No. 6, pp. 775–783.

Alam, K., Mitrofanov, A. and Silberschmidt, V.V., 2009. "Finite element analysis of forces of plane cutting of cortical bone". *Computational Materials Science*, Vol. 46, No. 3, pp. 738–743.

Albert, D., Katzenberger, M., Agnew, A. and Kemper, A., 2021. "A comparison of rib cortical bone compressive and tensile material properties: Trends with age, sex, and loading rate". *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 122, p. 104668. doi:10.1016/j.jmbbm.2021.104668.

Antich, P., Anderson, J., Ashman, R., Dowdey, J., Gonzales, J., Murry, R., Zerwekh, J. and Pak, C., 2009. "Measurement of mechanical properties of bone material in vitro by ultrasound reflection: Methodology and comparison with ultrasound transmission". *Journal of bone and mineral research : the official journal of the American Society for Bone and Mineral Research*, Vol. 6, pp. 417–26. doi:10.1002/jbmr.5650060414.

Ascenzi, A., Baschieri, P. and Benvenuti, A., 1994. "The torsional properties of single selected osteons." *Journal of biomechanics*, Vol. 27 7, pp. 875–84.

Ascenzi, M.G., Chin, J., Lappe, J. and Recker, R., 2015. "Non-osteoporotic women with low-trauma fracture present altered birefringence in cortical bone". *Bone*, Vol. 84. doi:10.1016/j.bone.2015.10.010.

Atthapreyangkul, A., Hoffman, M. and Pearce, G., 2021. "Effect of geometrical structure variations on the viscoelastic and anisotropic behaviour of cortical bone using multi-scale finite element modelling". *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 113, p. 104153. doi:10.1016/j.jmbbm.2020.104153.

Atthapreyangkul, A., Hoffman, M., Pearce, G. and Standard, O., 2022. "Effect of geometrical structure variations on strength and damage onset of cortical bone using multi-scale cohesive zone based finite element method". *Journal of the Mechanical Behavior of Biomedical Materials*, p. 105578. ISSN 1751-6161. doi:10.1016/j.jmbbm.2022.105578.

Audekercke, R. and Martens, M., 2018. *Mechanical Properties of Cancellous Bone*, pp. 89–98. ISBN 9781351074902. doi:10.1201/9781351074902-6.

Augustin, G., Davila, S., Mihoci, K., Udiljak, T., Vedrina, D.S. and Antabak, A., 2008. "Thermal osteonecrosis and bone drilling parameters revisited". *Archives of orthopaedic and trauma surgery*, Vol. 128, No. 1, pp. 71–77.

Awede, B., Berquin, A., Wuytack, F. and Lebacq, J., 1999. "Adaptation of mouse skeletal muscle to a novel functional overload test: Changes in myosin heavy chains and serca and physiological consequences". *European journal of applied physiology and occupational physiology*, Vol. 80, pp. 519–26. doi:10.1007/s004210050630.

B, R. and Huiskes, H., 2001. "Elastic constants of cancellous bone". doi:10.1201/b14263-19.

Bai, W., Shu, L., Sun, R., Xu, J., Silberschmidt, V.V. and Sugita, N., 2020. "Mechanism of material removal in orthogonal cutting of cortical bone". *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 104, p. 103618. ISSN 1751-6161. doi:10.1016/j.jmbbm.2020.103618.

Baro, D. and Deoghare, A.B., 2018. "Investigation of cutting force and temperature variation in orthogonal cutting of cortical bone". *Materials Today: Proceedings*, Vol. 5, No. 5, Part 2, pp. 12595–12608. doi:10.1016/j.matpr.2018.02.242. International Conference on Materials Manufacturing and Modelling, ICMMM - 2017, 9 - 11, March 2017.

Bayraktar, H.H., Morgan, E.F., Niebur, G.L., Morris, G.E., Wong, E.K. and Keaveny, T.M., 2004. "Comparison of the elastic and yield properties of human femoral trabecular and cortical bone tissue". *Journal of biomechanics*.

Bensamoun, S., Fan, S., Ilharreborde, B. and Rho, J., 2008. "Assessment of mechanical properties of human osteon lamellae exhibiting various degrees of mineralization by nanoindentation". *Journal of Musculoskeletal Research*, Vol. 11. doi:10.1142/S0218957708002024.

Bensamoun, S., Luu, S., Gherbezza, j.m. and Belleval, J.F., 2004. "Spatial distribution of acoustic and elastic properties of human femoral cortical bone". *Journal of biomechanics*, Vol. 37, pp. 503–10. doi:10.1016/j.jbiomech.2003.09.013.

Birnbaum, K., Sindelar, R., Gaertner, J. and Wirtz, D., 2001. "Material properties of trabecular bone structures". *Surgical and radiologic anatomy : SRA*, Vol. 23, pp. 399–407. doi:10.1007/s00276-001-0399-x.

Bohra, A., Chandrasekaran, M. and Teyi, N., 2019. "Bone drilling investigation and possible research: A state of the art review". Vol. 2128, p. 050022. doi:10.1063/1.5117994.

Bonadio, J., Jepsen, K.J., Mansoura, M.K., Jaenisch, R., Kuhn, J.L. and Goldstein, S.A., 1993. "A murine skeletal adaptation that significantly increases cortical bone mechanical properties. implications for human skeletal fragility." *The Journal of clinical investigation*, Vol. 92 4, pp. 1697–705.

Bumrerraj, S. and Katz, J., 2002. "Scanning acoustic microscopy study of human cortical and trabecular bone". *Annals of biomedical engineering*, Vol. 29, pp. 1034–42. doi:10.1114/1.1424908.

Casari, D., Michler, J., Zysset, P. and Schwiedrzik, J., 2021. "Microtensile properties and failure mechanisms of cortical bone at the lamellar level". Vol. 120, pp. 135–145. doi:10.1016/j.actbio.2020.04.030.

Chen, J., Yuan, D., Jiang, H., Zhang, L., Yang, Y., Fu, Y., Qian, N. and Jiang, F., 2021. "Thermal management of bone drilling based on rotating heat pipe". *Energies*, Vol. 15, p. 35. doi:10.3390/en15010035.

Childs, T. and Arola, D., 2011. "Machining of cortical bone: Simulations of chip formation mechanics using metal machining models". *Machining Science and Technology*, Vol. 15, No. 2, pp. 206–230.

Clarke, B., 2008. "Normal bone anatomy and physiology". *Clinical journal of the American Society of Nephrology : CJASN*, Vol. 3 Suppl 3, pp. S131–9. doi:10.2215/CJN.04151206.

Cook, R. and Zioupos, P., 2006. "The fracture toughness of cancellous bone". Vol. 39.

Cowin, S., 2001. *Bone mechanics handbook, second edition*.

Diab, T. and Vashishth, D., 2007. "Morphology, localization and accumulation of in vivo microdamage in human cortical bone". *Bone*, Vol. 40, pp. 612–8. doi:10.1016/j.bone.2006.09.027.

Eriksson, R., Albrektsson, T. and Magnusson, B., 1984. "Assessment of bone viability after heat trauma: a histological, histochemical and vital microscopic study in the rabbit". *Scandinavian journal of plastic and reconstructive surgery*, Vol. 18, No. 3, pp. 261–268.

Feldmann, A., Wili, P., Maquer, G. and Zysset, P., 2018. "The thermal conductivity of cortical and cancellous bone". *European Cells and Materials*, Vol. 35, pp. 25–33. doi:10.22203/eCM.v035a03.

Fonseca, E., Fernandes, M., Natal Jorge, R., Manzanares Céspedes, M.C. and Dias, M., 2018. "Effect of drill speed on the strain distribution during drilling of bovine and human bones". *Journal of Mechanical Engineering and Biomechanics*, Vol. Volume 2. doi:10.24243/JMEB/2.5.170.

Franzoso, G. and Zysset, P., 2009. "Erratum: "elastic anisotropy of human cortical bone secondary osteons measured by nanoindentation" [journal of biomechanical engineering, 2009, 131(2), p. 021001]". *Journal of biomechanical engineering*, Vol. 131, p. 117001. doi:10.1115/1.4000157.

Giesen, E., Ding, M., Dalstra, M. and J, E., 2002. "Mechanical properties of cancellous bone in the human mandibular condyle are anisotropic. response". *International Journal of Geographical Information Science - GIS*. doi:10.1016/S0021-9290(01)00228-7.

Gold, M., Munjal, A. and Varacallo, M., 2022. "Anatomy, bony pelvis and lower limb, hip joint". URL `http://europepmc.org/books/NBK470555`.

Hage, I.S. and Hamade, R.F., 2013. "Micro-fem orthogonal cutting model for bone using microscope images enhanced via artificial intelligence". *Procedia CIRP*, Vol. 8, pp. 385–390.

Halldin, A., Ander, M., Jacobsson, M. and Hansson, S., 2014. "On a constitutive material model to capture time dependent behavior of cortical bone". *World Journal of Mechanics*, Vol. 04, pp. 348–361. doi:10.4236/wjm.2014.411034.

Han, Y., Lv, Q., Song, Y. and Zhang, Q., 2022. "Influence of parameters on temperature rise and chips morphology in low-frequency vibration-assisted bone drilling". *Medical Engineering Physics*, Vol. 103, p. 103791. ISSN 1350-4533. doi:10.1016/j.medengphy.2022.103791.

Hasegawa, K., Turner, C. and Burr, D., 1994. "Contribution of collagen and mineral to the elastic anisotropy of bone". *Calcified tissue international*, Vol. 55, pp. 381–6. doi:10.1007/BF00299319.

Heydari, H., Kazerooni, N., Zolfaghari, M., Ghoreishi, M. and Tahmasbi, V., 2018. "Analytical and experimental study of effective parameters on process temperature during cortical bone drilling". *Proceedings of the Institution of*

Mechanical Engineers, Part H: Journal of Engineering in Medicine, Vol. 232, p. 095441191879653. doi:10.1177/0954411918796534.

Hillerya, M.T. and Shuaibb, I., 1999. "Temperature effects in the drilling of human and bovine bone".

Karaca, F., Aksakal, B. and Kom, M., 2011. "Influence of orthopaedic drilling parameters on temperature and histopathology of bovine tibia: An in vitro study". *Medical engineering physics*, Vol. 33, pp. 1221–7. doi: 10.1016/j.medengphy.2011.05.013.

Karalis T, G.P., 1982. "Research on the mechanical impedance of human bone by a drilling test". *Journal of Biomechanics*, Vol. 15, No. 8, pp. 561–581.

Katsamanis, F. and Raftopoulos, D.D., 1990. "Determination of mechanical properties of human femoral cortical bone by the hopkinson bar stress technique". *Journal of Biomechanics*, Vol. 23, No. 11, pp. 1173–1184. doi: 10.1016/0021-9290(90)90010-Z.

Khan, M., 2014. "3d finite-element modelling of drilling cortical bone: Temperature analysis". *Journal of Medical and Biological Engineering*. doi:10.5405/jmbe.1585.

Kim, T., See, C.W., Li, X. and Zhu, D., 2020. "Orthopedic implants and devices for bone fractures and defects: Past, present and perspective". Vol. 1, pp. 6–18. ISSN 2666-1381. doi:10.1016/j.engreg.2020.05.003.

Lee, J., Ozdoganlar, O. and Rabin, Y., 2012. "An experimental investigation on thermal exposure during bone drilling". *Medical engineering physics*, Vol. 34. doi:10.1016/j.medengphy.2012.03.002.

Lee, J., Rabin, Y. and Ozdoganlar, O.B., 2011. "A new thermal model for bone drilling with applications to orthopaedic surgery". *Medical engineering & physics*, Vol. 33, No. 10, pp. 1234–1244.

Lipson, S.F. and Katz, J.L., 1984. "The relationship between elastic properties and microstructure of bovine cortical bone." *Journal of biomechanics*, Vol. 17 4, pp. 231–40.

Liu, S., Wu, D., Zhao, J., Yang, T., Sun, J. and Gong, K., 2022. "Novel crescent drill design and mechanistic force modeling for thrust force reduction in bone drilling." *Medical engineering & physics*, Vol. 103, p. 103795.

Liu, x., Cohen, A., Shane, E., Yin, P., Stein, E., Rogers, H., Shiel, S., Mcmahon, D., Lappe, J., Recker, R., Lang, T. and Guo, X.E., 2010. "Bone density, geometry, microstructure, and stiffness: Relationships between peripheral and central skeletal sites assessed by dxa, hr-pqct, and cqct in premenopausal women". *Journal of bone and mineral research : the official journal of the American Society for Bone and Mineral Research*, Vol. 25, pp. 2229–38. doi:10.1002/jbmr.111.

Liu, Y., Luo, D. and Wang, T., 2016. "Hierarchical structures of bone and bioinspired bone tissue engineering." *Small*, Vol. 12 34, pp. 4611–32.

Lloyd, A., Gludovatz, B., Riedel, C., Luengo, E., Saiyed, R., Marty, E., Lorich, D., Lane, J., Ritchie, R., Busse, B. and Donnelly, E., 2017. "Atypical fracture with long-term bisphosphonate therapy is associated with altered cortical composition and reduced fracture resistance". *Proceedings of the National Academy of Sciences*, Vol. 114. doi: 10.1073/pnas.1704460114.

Luo, Y., Yinghua, R., Shu, Y., Mao, C., Zhou, Z. and Bi, Z., 2022. "Cutting behavior of cortical bone in different bone osteon cutting angles and depths of cut". *Chinese Journal of Mechanical Engineering*, Vol. 35, p. 91. doi: 10.1186/s10033-022-00769-2.

Luo, Y., 2017. *Bone Density and Mechanical Property*, pp. 31–44. ISBN 978-3-319-51669-1. doi:10.1007/978-3-319-51671-4_4.

Ma, S., Goh, E.L., Tay, T., Wiles, C., Boughton, O., Churchwell, J., Wu, Y., Karunaratne, A., Bhattacharya, R., Terrill, N., Cobb, J., Hansen, U. and Abel, R., 2020a. "Nanoscale mechanisms in age-related hip-fractures". *Scientific Reports*, Vol. 10. doi:10.1038/s41598-020-69783-5.

Ma, Z., Qiang, Z., Zhao, H., Piao, H. and Ren, L., 2020b. "Mechanical properties of cortical bones related to temperature and orientation of haversian canals". *Materials Research Express*, Vol. 7. doi:10.1088/2053-1591/ab6899.

McCalden, R.W., McGeough, J.A., Barker, M. and Court-Brown, C.M., 1993. "Age-related changes in the tensile properties of cortical bone. the relative importance of changes in porosity, mineralization, and microstructure." *The Journal of bone and joint surgery. American volume*, Vol. 75 8, pp. 1193–205.

McElhaney, J.H., 1966. "Dynamic response of bone and muscle tissue." doi:10.1152/jappl.1966.21.4.1231.

Meng, X., Qin, Q. and Qu, C., 2021. "Changes in bone's micromechanical properties caused by fatigue fracture". Vol. 231, No. 2, pp. 243–255. ISSN 1573-2673. doi:10.1007/s10704-021-00584-1.

Michimoto, I., Yano, K., Kobayashi, Y., Saito, K. and Matsukawa, M., 2020. "Effects of the cancellous bone structure in the skull on ultrasonic wave propagation". doi:10.21203/rs.3.rs-124985/v1.

Mirzaali, M.J., Schwiedrzik, J., Thaiwichai, S., Best, J., Michler, J., Zysset, P. and Wolfram, U., 2015. "Mechanical properties of cortical bone and their relationships with age, gender, composition and microindentation properties in the elderly". *Bone*, Vol. 93. doi:10.1016/j.bone.2015.11.018.

Morgan, E., Bayraktar, H. and Keaveny, T., 2003. "Trabecular bone modulus-density relationships depend on anatomic site". *Journal of biomechanics*, Vol. 36, pp. 897–904. doi:10.1016/S0021-9290(03)00071-X.

Morgan, E. and Keaveny, T., 2001. "Dependence of yield strain of human trabecular bone on anatomic site". *Journal of biomechanics*, Vol. 34, pp. 569–77. doi:10.1016/S0021-9290(01)00011-2.

Morgan, E., Unnikrishnan, G. and Hussein, A., 2018. "Bone mechanical properties in healthy and diseased states". *Annual Review of Biomedical Engineering*, Vol. 20, pp. 119–143. doi:10.1146/annurev-bioeng-062117-121139.

Moshage, S., McCoy, A. and Kersh, M., 2022. "Elastic modulus and its relation to apparent mineral density in juvenile equine bones of the lower limb". doi:10.31224/2684.

Natali, C., Ingle, P. and Dowell, J.K., 1996. "Orthopaedic bone drills-can they be improved? temperature changes near the drilling face." *The Journal of bone and joint surgery. British volume*, Vol. 78 3, pp. 357–62.

Odgaard, A., Kabel, J., van Rietbergen, B., Dalstra, M. and Huiskes, R., 1997. "Fabric and elastic principal directions of cancellous bone are closely related." *Journal of biomechanics*, Vol. 30 5, pp. 487–95.

Ovidiu, D., Leretter, M. and Neagu, A., 2014. "The quality of trabecular bone assessed using cone-beam computed tomography". *Romanian journal of biophysics*, Vol. Rom. J. Biopys., p. 227–241.

Panagiotopoulos, E., Kostopoulos, V., Tsantzalis, S., Fortis, A. and Doulalas, A., 2005. "Impact energy absorption by specimens from the upper end of the human femur". *Injury*, Vol. 36, pp. 613–7. doi:10.1016/j.injury.2004.10.014.

Reilly, D.T. and Burstein, A.H., 1975a. "The elastic and ultimate properties of compact bone tissue". Vol. 8, No. 6, pp. 393–405. ISSN 0021-9290. doi:10.1016/0021-9290(75)90075-5.

Reilly, D.T. and Burstein, A.H., 1975b. "The elastic and ultimate properties of compact bone tissue". *Journal of Biomechanics*, Vol. 8, No. 6, pp. 393–405. doi:10.1016/0021-9290(75)90075-5.

Reynolds, A., 2013. "The fractured femur." *Radiologic technology*, Vol. 84, pp. 273–291.

Rho, J.Y., Kuhn, L. and Zioupos, P., 1998. "Mechanical properties and the hierarchical structure of bone". *Medical engineering physics*, Vol. 20, pp. 92–102. doi:10.1016/S1350-4533(98)00007-1.

Robins, S. and Bailey, A., 1972. "Age-related changes in collagen: The identification of reducible lysine-carbohydrate condensation products". *Biochemical and Biophysical Research Communications*, Vol. 48, No. 1, pp. 76–84. doi: 10.1016/0006-291X(72)90346-4.

Robles Linares Alvelais, J., Axinte, D., Liao, Z. and Gameros, A., 2021. "Machining-induced thermal damage in cortical bone: Necrosis and micro-mechanical integrity". *Materials design*, Vol. 197. doi:10.1016/j.matdes.2020.109215.

Rodriguez-Florez, N., Oyen, M. and Shefelbine, S., 2012. "Insight into differences in nanoindentation properties of bone". *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 18, pp. 90–99. doi:10.1016/j.jmbbm.2012.11.005.

Ross, P.D., Davis, J.W., Epstein, R.S. and Wasnich, R.D., 1991. "Pre-existing fractures and bone mass predict vertebral fracture incidence in women." *Annals of internal medicine*, Vol. 114 11, pp. 919–23.

Roy, M.E., Rho, J.Y., Tsui, T.Y., Evans, N.D. and Pharr, G.M., 1999. "Mechanical and morphological variation of the human lumbar vertebral cortical and trabecular bone". *Journal of biomedical materials research*, Vol. 44, No. 2, pp. 191–197.

Samarasinghe, C., Uddin, M., Bari, S. and Xian, C., 2021. "Temperature and force generation in surgical bone drilling". Vol. 2324, p. 060007. doi:10.1063/5.0037543.

Samarasinghe, C., Uddin, M., Bari, S. and Xian, C., 2019. "Surgical bone drilling: A review". In *ASME International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, Vol. 59407, p. V003T04A054.

Santiuste, C., Rodríguez-Millán, M., Giner, E. and Miguélez, H., 2014. "The influence of anisotropy in numerical modeling of orthogonal cutting of cortical bone". *Composite Structures*, Vol. 116, pp. 423–431.

Shihao, L., Shu, L., Kizaki, T., Bai, W., Terashima, M. and Sugita, N., 2021. "Cortical bone drilling: A time series experimental analysis of thermal characteristics". *Journal of Manufacturing Processes*, Vol. 64, pp. 606–619. doi: 10.1016/j.jmapro.2021.01.046.

Sroga, G. and Vashishth, D., 2012. "Effects of bone matrix proteins on fracture and fragility in osteoporosis". *Current osteoporosis reports*, Vol. 10, pp. 141–50. doi:10.1007/s11914-012-0103-6.

Stauber, M. and Müller, R., 2006. "Age-related changes in trabecular bone microstructures: Global and local morphometry". *Osteoporosis international : a journal established as result of cooperation between the European Foundation for Osteoporosis and the National Osteoporosis Foundation of the USA*, Vol. 17, pp. 616–26. doi: 10.1007/s00198-005-0025-6.

Sugita, N. and Mitsuishi, M., 2009. "Specifications for machining the bovine cortical bone in relation to its microstructure". *Journal of biomechanics*, Vol. 42, No. 16, pp. 2826–2829.

Sugita, N., Osa, T., Aoki, R. and Mitsuishi, M., 2009. "A new cutting method for bone based on its crack propagation characteristics". *CIRP annals*, Vol. 58, No. 1, pp. 113–118.

Sui, J., Sugita, N., Ishii, K., Harada, K. and Mitsuishi, M., 2013. "Force analysis of orthogonal cutting of bovine cortical bone". *Machining Science and Technology*, Vol. 17, No. 4, pp. 637–649.

Tsou, A.C., 2003. "Ash content modulation of torsionally derived effective material properties in cortical mouse bone". *Journal of Biomechanical Engineering*, Vol. 125, p. 615. doi:10.1115/1.1611513.

Udiljak, T., Ciglar, D. and Skoric, S., 2007. "Investigation into bone drilling and thermal bone necrosis". *Advances in Production Engineering Management*, Vol. 2, pp. 103–112.

van der Meulen, M., Jepsen, K. and Mikić, B., 2001. "Understanding bone strength: Size isn't everything". *Bone*, Vol. 29, pp. 101–4. doi:10.1016/S8756-3282(01)00491-4.

Vashishth, D., Gibson, G., Khoury, J., Schaffler, M., Kimura, J. and Fyhrie, D., 2001. "Influence of nonenzymatic glycation on biomechanical properties of cortical bone". *Bone*, Vol. 28, pp. 195–201. doi:10.1016/S8756-3282(00)00434-8.

Wang, H., Gao, X., Wang, B., Wang, M., Liu, Y., Zan, T., Gao, P. and Liu, C., 2022. "Evaluation of temperature distribution for bone drilling considering aging factor". *Medicine in Novel Technology and Devices*, Vol. 16, p. 100174. doi:10.1016/j.medntd.2022.100174.

Wang, W., Shi, Y., Yang, N. and Yuan, A., 2013. "Experimental analysis of drilling process in cortical bone". *Medical engineering physics*, Vol. 36. doi:10.1016/j.medengphy.2013.08.006.

Wang, X., Li, Y., Hodgson, P. and Wen, C., 2007. "Nano- and macro-scale characterisation of the mechanical properties of bovine bone". *Materials Forum*, Vol. 31, pp. 156–159.

Yang, Y., Chengyong, W., Qin, Z., xu, L., Song, Y. and Chen, H., 2010. "Drilling force and temperature of bone by surgical drill". *Advanced Materials Research*, Vol. 126-128, pp. 779–784. doi:10.4028/www.scientific.net/AMR.126-128.779.

Yeni, Y., Dong, N., Fyhrie, D. and Les, C., 2004. "The dependence between the strength and stiffness of cancellous and cortical bone tissue for tension and compression: Extension of a unifying principle". *Bio-medical materials and engineering*, Vol. 14, pp. 303–10.

Zawadzki, P., Talar, R., Patalas, A. and Legutko, S., 2022. "Influence of machining parameters on cutting and chip-formation process during cortical bone orthogonal machining". *Materials*, Vol. 15, p. 6414. doi:10.3390/ma15186414.

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