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Direction-dependent analysis of force and torque in conventional and ultrasonically-assisted drilling of cortical bone

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Abstract. Bone drilling is a common surgical procedure in orthopaedic, neuro, and dental surgeries for internal fixation. Estimation and control of the bone drilling force and torque are critical in preventing drill breakthrough, excessive heat generation and unnecessary mechanical damage to the bone. This paper illustrates experimental measurements, and a comparison of the drilling thrust force and torque in Conventional Drilling (CD) and Ultrasonically-Assisted Drilling (UAD), in two directions; along the longitudinal axis of the bone and normal to it (radial direction). The objective of this research is to find the effect of drill size and ultrasonic vibration superimposed on drill movement, on the thrust force and torque. The effect of drill speed on force was investigated in the described directions, followed by a series of experiments, to explore the influence of drill size and penetration direction on the level of force and torque. The drilling force and torque were found to be strongly dependent on the drilling direction. Experimental results reveal that when drilling in a specific direction, lower drilling force and torque are found in UAD compared to CD.

1. Introduction

Bone drilling with surgical hand drills is an established procedure in orthopaedic, neuro, dental, and reconstructive surgery. A considerable amount of pressure is required by the surgeon to push the drill when drilling in the harder portion of the bone. Wiggins and Malkin [1] showed that the drilling force and torque produced in the process is a consequence of excessive friction and flute clogging caused by segmented chips. Larger drilling forces are malignant to tissue, like bone, and cause discomfort to the operator. Another consequence of the drilling process is the torque, which may cause frequent drill breakage during surgical procedures [2-4]. A number of factors influencing bone drilling force include specimen type, location, direction of cutting, drill size and drill speed. Lower drilling force is important, both for safe surgical procedures and for the surgeon's ease. Quantitative analysis of bone drilling force is essential, as it drastically affects bone temperature, which is the primary source of inducing thermal damage in bone [5-7].

Drilling force and torque have been the focus of many studies. Besides experimental work, the process has been extensively researched for the prediction of force and torque through finite element analysis, analytical modeling, and haptic simulations [8-10]. Current technological improvement in the area is the development of real-time breakthrough detection systems as a safety enhancement [11-13]. Such systems are useful in preventing drill breakage and encouraging

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control of the drill in the penetration of bone tissue. Despite such technological enhancement, the issues of size, safety, and cost associated with these systems still limit their use in clinical practice. Recently, Alam et al. [14] have proposed UAD as an alternative to minimize drilling thrust force, torque, associated stress in bone tissue, and better surface finish compared to CD. In previous related studies, the use of ultrasonic cutting in bone was limited to only the chisel-like action of the tool [15,16]. Li et al. [17] showed a better material removal rate and lower cutting force using ultrasonics in machining ceramic matrix composites. Some recent studies modeled the ultrasonically-assisted cutting of soft materials and bone using the finite element method [18,19].

The surgeon inserts the drill into the bone in different directions relative to the fracture site. Since the anisotropic nature of cortical bone is well established [20], it is necessary to investigate the level of drilling force and torque in different directions. To my knowledge, there has been no study performed, to date, that measures and analyzes the bone drilling force and torque produced when drilling in a direction parallel to the bone axis, using different sizes of drill. Further, the benefits of UAD have not been explored in the prescribed direction. In this paper, the shortcomings of previous studies are discussed, and a series of experiments are conducted to explore the hidden mechanics of the bone drilling process in the two directions described earlier. Experimental results show that the size and speed of the drill significantly affect thrust force and torque when drilling in both directions. Further, UAD is found useful in reducing thrust force and torque, regardless of the drilling direction.

2. Drilling experiments

2.1. Bone specimen for drilling

The choice of bone for the drilling experiments was the middle compact portion (cortical bone) of a fresh cow femur. The approximate age of the animal was between two to three years. Allotta et al. (1997) [21] reported that bovine bone is similar to human bone in geometry and material properties. A total of fifteen fresh femur bones were obtained from a butcher shop, and those having internal damage in the compact portion were rejected. The soft tissue (periosteum) was removed from the top surface of the femurs, as they become trapped in the flues of the drill. Specimens were refrigerated at -10°C, before the experiments, to preserve their properties. The average length of each specimen was 60 mm, and average wall thickness was 8 mm to 9 mm. Each specimen accommodated around forty holes in the radial direction and ten to twelve holes in the longitudinal direction.

2.2. Experimental equipment

A test rig originally designed for ultrasonically-assisted machining of metals with autoresonant control was used in the experiments. The ultrasonic system can be attached to a standard lathe or drilling machine for various machining operations with specially designed attachments. The drilling force and torque generated during CD and UAD were measured using the experimental arrangement shown in Figure 1(a). The force and torque data were acquired using a two-component dynamometer (Kistler type 9271A). The force and torque signals were conditioned using Kistler charge amplifiers and were captured using a digital oscilloscope. The Picoscope series 2000 oscilloscope, with a maximum frequency of 10 MHz, was used for acquiring the force and torque in a digital format. The ultrasonic transducer was gripped in the chuck of a CNC drilling machine, while the bone was fixed in the holding device mounted on the dynamometer. The directions of drilling and ultrasonic vibrations are shown in Figure 1(b).

Transducers used in ultrasonic machining convert electrical energy into mechanical motion, and can be based on piezoelectric principles. The schematic of the ultrasonic cutting system and its components is shown in Figure 2. The main elements of a UAD system are:

(i) A high frequency generator;

(ii) A transducer, which utilizes piezoelectric effect;

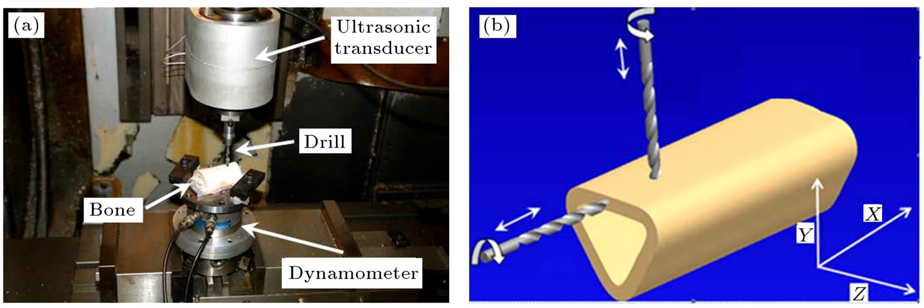

Figure 1. (a) Experimental set up for bone drilling. (b) Cortical bone and drilling directions. X: longitudinal direction (bone axis), Y: radial direction, Z: transverse direction.

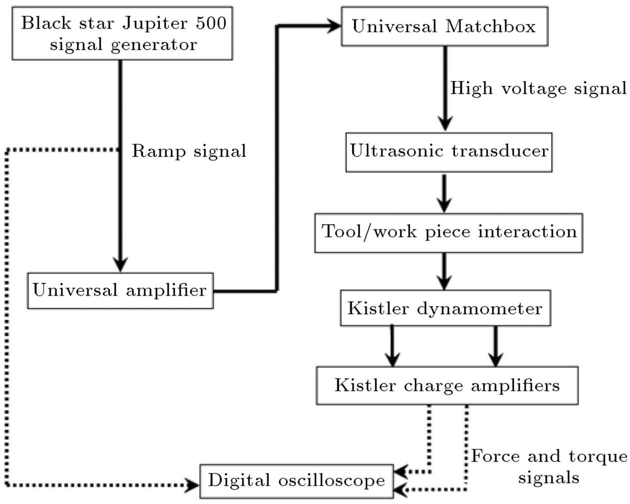

Figure 2. Components of ultrasonically-assisted cutting system [14].

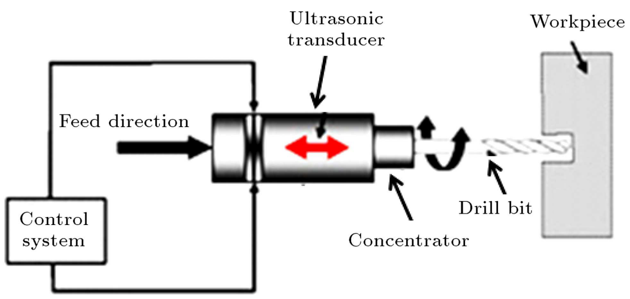

Figure 3. Construction of ultrasonically-assisted drill [14].

(iii) A concentrator, which is shaped to amplify the vibration output of the transducer;

(iv) A tool holder;

(v) A drill.

The system can generate a frequency that is enough to vibrate a drill at maximum frequency of 50 kHz. A sevenfold increase in vibration amplitude of up to 20 micrometers could be obtained with a suitably shaped concentrator. The construction of the ultrasonic drill is illustrated in Figure 3.

2.3. Drilling procedure

The choice of drilling speed, drill size and feed rate were based on values widely reported in literature related to bone drilling [7,22-24]. The drilling speed was varied between 600 rpm and 3000 rpm. The ultrasonic frequency and amplitude of the vibrations were kept at 20 kHz and 10 micrometers, respectively, in UAD. All experiments were conducted in the absence of external cooling, since the splashing of the fluid may be a potential bio hazard to the operator. However, a spray of water was regularly used to avoid the dryness of specimens. Four different sizes of drill, ranging from 2 mm to 4 mm, were used. Each

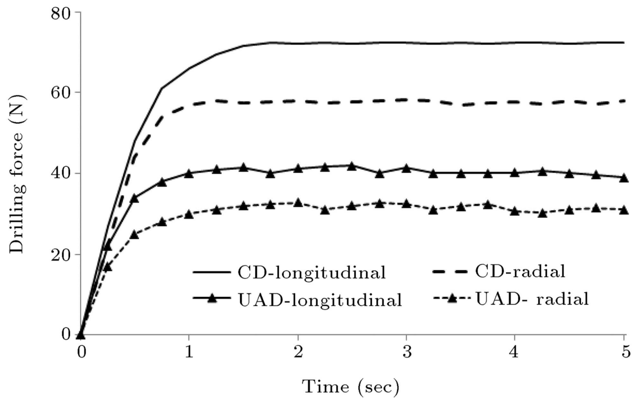

Figure 4. Evolution of drilling thrust force in two directions with and without ultrasonic vibrations (drill diameter: 4 mm, drill speed: 1800 rpm).

experiment was repeated five times for a specific set of parameters to represent repeatability in measurements. The cutting direction in the experiments was parallel to the principal direction of the osteons (longitudinal direction) and normal to it (radial direction).

3. Results and discussions

3.1. Drilling force evolution in bone

The force and torque produced during drill penetration was measured in the direction perpendicular (radial) and parallel to the longitudinal axis of the bone. The drill penetrated through the whole thickness of the cortical wall when drilling in the radial direction. In the longitudinal direction, it only descended approximately 10 mm, due to the non-uniform cross-section of the bone in that direction. A typical force-time graph obtained from the measurement system when drilling in both directions is shown in Figure 4. A small oscillation in the force profile, due to the vibrations in the drilling equipment and the sensitivity of the dynamometer, were recorded and removed in the force evolution curves (see Figure 4). The force was observed to develop quickly and attained a plateau in both types of drilling and direction, as contact between the drill and bone was initiated. UAD produced a lower level of force compared to CD when drilling in both directions. The influence of drilling speed, ultrasonic vibration, and drill size on force and torque is discussed in the next section.

3.2. Effect of drill speed on force

The effect of drill speed on drilling force in both directions, with and without ultrasonic vibrations, was studied. A comparison of thrust force for both drilling techniques and directions are shown in Figure 5(a) and (b). Experimental results showed a significant difference in the forces experienced by the drill in both types of drilling and direction for the range of drilling speeds used. Interestingly, the drilling force in the

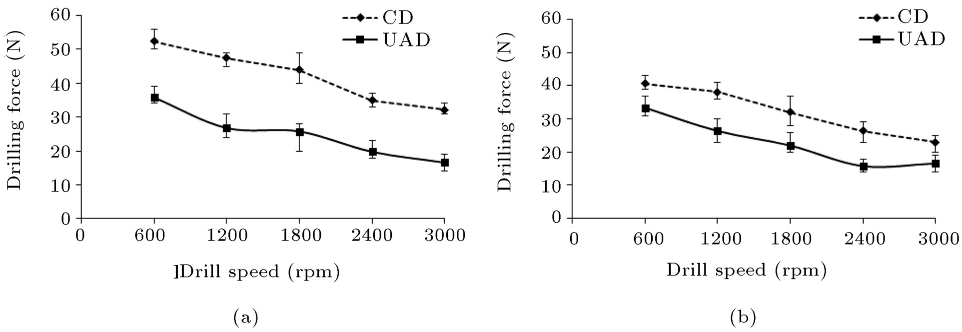

Figure 5. Variation of thrust force with drilling speed in CD and UAD: (a) Longitudinal direction; and (b) radial direction (drill diameter: 3 mm).

longitudinal direction was higher than in the radial direction in both types of drilling and for all drilling speeds. At the microstructure level, cortical bone is similar to unidirectional fiber reinforced composite, where fibers (osteons) run predominantly parallel to the longitudinal axis of the bone in a matrix material known as interstitial bone. The higher level of force may be attributed to the increased resistance of osteons in compression, or buckling upon the drill load in the longitudinal direction.

The drop in force with increasing drill speed was attributed to the thermal softening of the bone material due to higher cutting speeds, as described by Alam et al. [14]. The experimental results of CD obtained from this study were consistent with those reported by Hillery and Shuaib [22], where thrust force measured in the radial direction was shown to drop exponentially by increasing speed when drilling the cortical bone. In that study, thrust force was dropped from 48 N to 23 N, when drilling speed was increased from 400 rpm to 2000 rpm. The results of this study are also consistent with those reported by Jacob et al. [24]. In this study, UAD resulted in lower drilling force in both directions. The obvious reason was the improved chip evacuation from the drilling zone using the UAD technique. Due to intermittent contact between the drill and bone in UAD, the production of powder-like chips avoided flute clogging. The nature of chip separation and evacuation from the drilling zone in CD was different from that in UAD. CD produced long spiral chips, which were seen to clog the flutes of the drill during evacuation from the drilling zone. In UAD, on the other hand, high frequency vibrations of the drill reduced the average friction between the drill and bone compared to CD. The percent reduction in force caused by UAD was more in the longitudinal direction, compared to the radial direction, for all drilling speeds.

3.3. Effect of drill size on force and torque

To investigate the effect of drill size on force and torque, the drill speed was kept constant at 1800 rpm. The drilling force was strongly influenced by the drill diameter and was found to increase linearly with increasing drill size. This was due to the larger sharing volume of the material cut by the cutting edges of the larger drill size compared to the smaller one. The increase in frictional effect (due to the larger drill-bone area of contact) using the large drill size was also a contributing factor. The trend in force increase was similar in both drilling directions, as shown in Figure 6(a) and (b). An increase of 450% and 230%, respectively, was observed when the drill size varied from 2 mm to 4 mm in CD and UAD in the longitudinal direction. A similar trend was also noted in the radial direction.

The drill size up to 2 mm produced comparatively lower force in both types of drilling, as well as direction. This may be explained by the fact that fewer osteons were sheared by the smaller cutting edges of the drill. The effect of ultrasonic vibration was

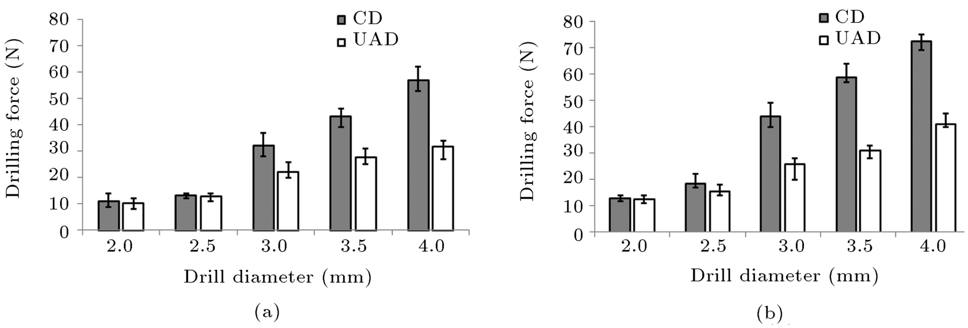

Figure 6. Variation of thrust force with drill size in CD and UAD: (a) Radial direction; and (b) longitudinal direction.

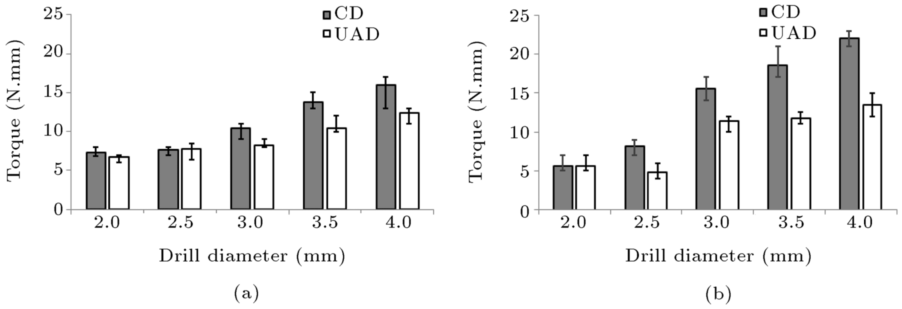

Figure 7. Variation of torque with drill size in CD and UAD: (a) Radial direction; and (b) longitudinal direction.

insignificant using drill sizes of 1.5 mm and 2 mm. This may be due to the buckling of the drills caused by compressive loading, which produced lateral deflection. Such deflection could not transfer vibrations efficiently on the longitudinal axis of the drill, and, hence, did not improve its performance in cutting. In a recent study by Alam et al. [14], the drilling thrust force and torque were found to be inversely related to the change in vibrational frequency and amplitude in UAD of cortical bone in the radial direction.

The effect of drill size and ultrasonic vibration on torque was also investigated. A linear relationship was found between the torque and drill diameter in CD and UAD, in both directions. The effect of drill size on the torque using CD and UAD in both directions are shown in Figure 7(a) and (b). Like the drilling force, torque was lower in the radial direction compared to the longitudinal direction in both types of drilling. UAD did not provide any benefit in reducing torque in both directions when a drill size of 2 mm was used. The exact reason for this phenomenon was unclear to the author at this stage of investigation; however, this may be due to the local sliding of osteons over the cutting edge of the smaller size drill. In a previous study by Hillery and Shuaib [22], torque was measured in the radial direction and was observed to drop from 48 Nmm at 400 rpm to 23 Nmm at 2000 rpm. It was expected that the drilling force and torque would decrease in both types of drilling and direction if a coolant was used in the experiments. This is because the cooling medium (fluid) would reduce friction between the drill and the bone, thus, allowing the drill to penetrate with less effort compared to that under dry conditions. The application of coolant would also result in lower temperature in the drilling zone.

4. Conclusions

The main aim of this analysis was to find the effect of drill size and ultrasonic vibration imposed on a drill, on the drilling force and torque in two principal directions. Particular attention was paid to the benefits of UAD and to the nature of the obtained improvements in the cutting of bone compared to CD. A multifold decrease in force and torque was measured when drilling in both directions using the UAD technique. Bone drilling force and torque were strongly dependent on drill size and drilling direction. The decrease in force and torque using a vibrating drill was the consequence of the improved chip separation process in UAD. The benefit offered by UAD in reducing cutting force and torque was limited to a drill size of 2.5 mm and above.

The main aim of this research study was to obtain in-depth knowledge of the mechanics of drill penetration in cortical bone tissue with conventional and vibrated modes, and to provide engineering-based information for the medical community, in order to improve current surgical procedures. It is expected that ultrasonic drilling will minimize the efforts of a surgeon and provide smooth penetration of drill in bone, without or with minimum invasion. Since imposing ultrasonic vibration on the drill significantly reduced the force and torque, it may be employed in orthopaedic or related surgical procedures with lower cost. Such hand drills will replace expensive experimental equipment or robot-assisted surgical systems in clinics. Further experiments are required to investigate the effect of ultrasonic vibration on the level of heat generation in bone, prior to the utilization of ultrasonic drills in orthopaedics or related surgery.

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Biography

Khurshid Alam received his BEng degree in Mechanical Engineering from the University of Engineering and Technology, Peshawar, Pakistan, his MS degree in Design and Manufacturing from the GIK Institute of Engineering Sciences and Technology, Topi, Pakistan, and his PhD degree in Mechanical Engineering from Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK. He is currently Assistant Professor in the Department of Mechanical and Industrial Engineering, Sultan Qaboos University, Sultanate of Oman. His research interests are mainly focused on experimental measurement and computational analysis of bone cutting forces using conventional and vibrational cutting techniques, and experimental and computational modeling of biomechanical components and systems.