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Quantitative Analysis of Force and Torque in Bone Drilling

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Abstract: Bone drilling is an important and the most frequent operation in orthopaedics and other bone surgical procedures. Prediction and control of drilling force and torque are critical to safe and efficient surgeries. This paper studies the drilling force and torque arising from bone drilling process. Drilling parameters such as drilling speed, feed rate, drill size and drill condition (sharp and worn) were changed to measure the force and torque in the direction of the drill penetration. Experimental results demonstrated lower drilling force using a sharp drill compared to a worn drill for similar drilling conditions. Contrary to the drilling force, lower torque was measured using a worn drill compared to a sharp drill. The drilling force was found to decrease with increase in drill speed and increased with rise in the feed rate using both types of drills. A linear drop in drilling torque was measured with increase in drilling speed. This study provided scientific information to orthopaedic surgeons and technicians to use appropriate surgical drill and cutting parameters to avoid overstressing of the bone tissue and drill breakage during drilling operations.

Keywords: Orthopaedic, Bone drilling, Drilling force, Drilling torque, Drill wear.

التحليل الكمي للقوة والعزم المصاحبتين للحفر في العظام

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الملخص: الحفر في العظام ظاهرة تستحق الدراسة لأهميتها ولكونها مصاحبة لعمليات تقويم العظام وغيرها من العمليات الجراحية التي تتطلب التعامل مع العظام. ويعتبر التوقع والتحكم بالقوة والعزم أثناء الحفر مهماً لإجراء هذه العمليات بكفاءة وسلامة. هذه المقالة تعنى بدراسة القوة والعزم المصاحبين لعملية الحفر في العظام. المتغيرات الوسيطة المعرفة لعملية الحفر مثل سرعة الحفر، سرعة التغذية، سعة الحفر وحالة المثقاب (من حيث كونه حاد أو مهترئ) تم التحكم بها مع قياس القوة والعزم في اتجاه الاختراق أو التغلغل. نتائج التجارب أظهرت ان قوة أقل نتجت عن استخدام مثقاب حفر حاد مقارنة بمثقاب حفر مهترئ. بينما العزم اللازم للحفر أظهر علاقة معاكسة، حيث كان العزم أقل في حالة المثقاب المهترئ. قوة الحفر انخفضت مع زيادة سرعة الحفر وارتفعت مع زيادة سرعة التغذية. بينما انخفض العزم خطيا مع زيادة السرعة. نتائج هذه الدراسة يمكن الاستئناس بها من قبل جراحي العظام والمهندسين لحسن استخدام مثقاب الحفر لتجنب الإفراط في اجهاد أنسجة العظام ولتجنب كسر أدوات الحفر.

الكلمات المفتاحية: جراحة العظام، حفر العظام، قوة الحفر، العزم، اهتراء مثقاب الحفر.

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1. Introduction

Cutting bone for fixation is one of the oldest surgical procedures in the history of medicine. It is believed that an operation to remove a portion of the skull bone was performed as early as 10,000 B.C. (Krause 2003). In modern times, bone fracture is a feature of everyday life due to accidents or aging, and fusing bone fragments together or replacing human joints usually requires cutting bone. Knee and hip implant surgeries are frequently performed around the world, with a total of 300,000 knee arthroplasties performed each year in the United States alone (Harrysson *et al*. 2007). Popular methods of bone cutting include scraping, grooving, sawing, and drilling. Among these methods, drilling is a surgical technique which is frequently and widely discussed in the literature (Alam 2014; Alam *et al*. 2011a; Alam *et al*. 2014b; Augustin *et al*. 2012; Pandey and Panda 2013). Measurements of forces and temperatures in bone drilling operation have been discussed widely in the literature (Abouzgia and Symington 1996; Alam *et al*. 2011b; Alam *et al*. 2015; Alam and Silberschmidt 2014; Bachus *et al*. 2000; Brisman 1996). Like drilling of other materials (Muhammad *et al*. 2010; Muhammad *et al*. 2011; Muhammad *et al*. 2012), bone drilling requires force to push the tool into the bone. Lower cutting forces in bone surgical procedures are required to avoid unnecessary damage to the bone tissue.

Elevated temperature is harmful for bone tissue since it causes death in living cells. Several empirical studies have found that the bone temperatures in drilling operation are strongly correlated with drilling force (Abouzgia and Symington 1996; Bachus *et al*. 2000; Brisman 1996; Matthews and Hirsch 1972). The application of heavy force on the drill can reduce both the maximum cortical temperature and its duration above 50^{o}C (Bachus *et al*. 2000). An increase in bone temperature was observed with an increase in drilling force from 1.5–4 N (Brisman 1996). Some empirical studies have shown that cortical bone temperatures are inversely related to drilling force. Matthews and Hirsch (1972) found an inverse relationship between drilling force and bone temperature using force levels ranging from 20–118 N while drilling human cortical bone. In that study, the decrease in bone temperature was attributed to the reduced time necessary to penetrate the drill into the cortex of the bone. Abouzgia and Symington (1996) found that both maximum temperatures and the duration of application decreased when drilling force was increased from 1.5 N to 9.0 N. Allan *et al*. (2005) presented a relationship between the level of drill bit wear and the temperature of the bone being drilled.

Bone tissue is sensitive to many osteotomes. Bone cracking under sharp tool penetration is a common phenomenon and has been extensively studied previously (Sugita *et al*. 2009; Alam *et al*. 2012; Alam *et al*. 2014a). In a bone drilling operation, an orthopedic surgeon pushes the drill into the bone with a significant amount of force. Harvesting long bone grafts may also cause pain due to stress fractures in the bone around the donor site (Tanishima *et al*. 1995). Heavy drilling force may induce microcracks and impart damage to the surrounding tissue (Brett *et al*. 2004; Kendoff *et al*. 2007). In addition, heavy drilling force and torque are the prime reasons for drill breakage during surgical procedures (Jantunen 2002). Lower cutting force was also measured in plane cutting of cortical bone in the presence of imposed vibrations on the cutting tool (Alam *et al*. 2013). Perhaps in response to these findings, some recent studies have proposed ultrasonically-assisted drilling (UAD) of bone to minimize drilling force, torque, temperature, and micro cracks (Alam *et al*. 2011b; Alam *et al*. 2014a; Alam and Silberschmidt 2014; Wang *et al*. 2013). Some studies have also attributed lower force to appropriate drill geometry and drilling parameters (Wiggins and Malkin 1976; Saha *et al*. 1982).

Heavy drilling force could damage bone tissue and adversely affect the success of a surgical procedure. Recent technological advancements have been concerned with efforts to decrease the force required by a surgeon when cutting bone, thereby expediting surgical procedures without compromising safety. Conventional surgical tools are continually replaced by robot-assisted tools for achieving safety and performance goals, but bone drilling is mostly performed using handheld surgical drills with no detection system to measure force and torque. Despite technological enhancement in bone surgical procedures, metallic drills are still the primary choice of orthopedic surgeons. The cutting performance of surgical drills dramatically drops when sharp cutting edges of the drill wear out. As a result, surgical clinics spend heavily to replace surgical tools when they wear out. No study performed has provided a comparison between the level of force and torque produced by a sharp and worn drill. This study is a step forward; therefore, to measure and compare the drilling thrust force and torque generated using a sharp versus worn drill. The effect of drilling parameters such as drilling speed and feed rate on the drilling force for both sharp and worn drills is studied using a series of experiments discussed below.

2. Materials and Methods

2.1. *Specimen Preparation*

Drilling tests were performed on compact bone excised from a bovine femoral shaft. Fresh femurs of a young cow with no visible disease were obtained from a local slaughter house. The middle portions of the femurs were cut using a mechanical hacksaw. Water irrigation was used while cutting the specimen from the femoral shaft in order to avoid damage to the bone tissue. Specimens of cylindrical shape (Fig. 1a) were obtained for the drilling operation. Specimens were kept refrigerated at -10°C for two days before using them. The thin, elastic film (periosteum) was removed from the top surface of the bone to prevent clogging of the drill flutes. Each cylindrical specimen was cut into two halves for attaching them to a metallic plate with glue. This was done to secure the bone specimen firmly to a fixture during drilling tests. Test specimen attached to metallic plate is shown in Fig. 1b.

2.2. *Experimental Setup and Procedure*

The experimental setup consisted of a vertical CNC drilling machine, a stationary dynamometer (Type 9271A) and surgical drill bits (Kistler Group AC, Winterthur, Switzerland). The dynamometer measures both the thrust force and torque as a function of time and was placed directly below the sample for drilling. Piezoelectric materials were used in the sensors, generating a charge proportional to the applied load. The torque was not measured directly but instead was calculated from the various measurement signals of the force sensors. Charge amplifiers were used to charge the difference arising when sensors were loaded. The charge signals were then converted into equivalent voltage signals. Two sizes of orthopedic drills (2.5 mm and 4.8 mm in diameter) (Zimmer Biomet, Warsaw, Indiana, USA) donated by a local hospital were used in the experiments. The sizes of drills used in the current study were within the range reported in the literature related to bone drilling and are frequently used in surgical clinics (Alam 2014; Alam *et al*. 2014b; Augustin *et al*. 2012; Hillery and Shuaib 1999). Drill bits' geometrical angles included a 90-degree point angle, 20-degree helix angle, and a 116-degree chisel edge angle. Both sharp drills and worn drills of the prescribed sizes were used. The bone surgical drill bits used in the experiments are shown in Fig. 2. According to hospital sources, drills are considered worn after drilling approximately 500–600 holes. The rigid structure and high power of the drilling machine enable precise identification of drilling speed and feed rate. The Picoscope series 2000 oscilloscope with a maximum frequency of 10 MHz was used to acquire the data for force and torque in a digital format (Pico Technologies, Cambridgeshire, UK).

Drilling tests were conducted at room temperature (25°C). Drill penetration was performed perpendicular to the major

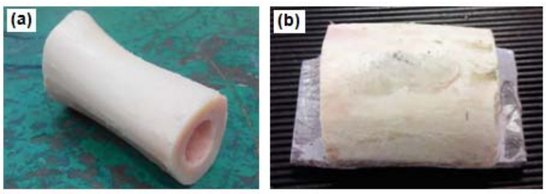

Figure 1. Bone specimen used in drilling experiments, (a) specimen excised from femur, and (b) specimen attached to metallic plate.

Figure 2. Orthopaedic surgical drills used in drilling experiments.

anatomical direction of the bone, along the longitudinal axis of the femur bone. Room temperature tap water was continually supplied to the drilling region to mimic *in vitro* drilling conditions. Each drill was replaced after boring 40 holes in order to get reliable force data for comparison. A maximum drilling speed and feed rate of 3,000 rpm and 50 mm/min, respectively, were used in experiments. Ten samples were prepared for drilling operation. Each sample accommodated twenty holes on average. Each experiment was repeated three times for a particular set of drilling parameters to observe repeatability in the measurements. The experimental setup for bone drilling is shown in Fig. 3.

3. Results and Discussion

Force evolution during drill penetration was studied. The force was observed to rise rapidly when the drill bit started penetrating the bone. The force attained maximum value when the cutting lips of the drill were fully engaged with the bone and remained constant until the drill crossed the cortex of the bone. The force evolution with respect to the drilling time using a worn and sharp drill is shown in Fig. 4. Similar force profiles were observed in all drilling tests. All the data points in the subsequent plots represent the maximum value of the force obtained during drill penetration. The drilling thrust force (the force component in the direction of drilling) and torque (the moment about the axis of rotation of the drill) were measured. Each data point in the subsequent plots showed an average of the three consecutive drilling tests. The standard error was plotted for each set of drilling tests to show variation from the mean value. The effect of drilling speed, feed rate on thrust force, and drilling speed on torque is discussed below.

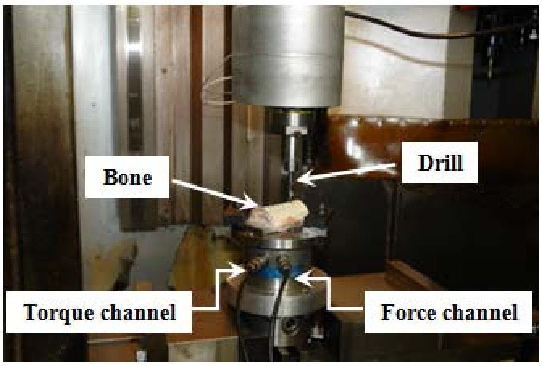

Figure 3. Experimental set up for bone drilling.

3.1. Effect of Drilling Speed on Force

The effect of drilling speed on force was studied. Drilling was performed for a set of parameters using a sharp drill followed by a worn drill. The drilling speed was changed from 600 rpm to 3,000 rpm, and the feed rate was kept constant at 30 mm/min. Figures 5 and 6 show the plots of drilling thrust force for different drilling speeds using both types and sizes of drills. It was observed that the thrust force decreased with the progressive increase in drill speed. The thrust force was observed to decrease by 32% (from an average maximum force of 67 N to 45 N) when the drilling speed was increased from 600 rpm to 3,000 rpm using a 4.8-mm worn drill (Fig. 5). Similarly, a decrease of 33% (from an average maximum force of 51 N to 34 N) was noted for a similar change in drilling speed when a sharp drill was used. The force dropped from 67 N to 51 N when the drill was changed from worn to sharp using 600 rpm and a 4.8-mm drill. At the higher drilling speed used in this study (3,000 rpm), for the same size of drill the force was dropped from 45 N to 34 N. A comparison of a sharp and worn drill showed a similar trend using a 2.5-mm diameter drill. A decrease of 23% was measured when a 2.5-mm worn drill was replaced with a sharp drill of the same size using 600 rpm (Fig. 6). Approximately the same drop was measured when 3,000 rpm were used. Although not shown here, the drop in the force with an increase in the drill speed was observed for the range of feed rates used in this study.

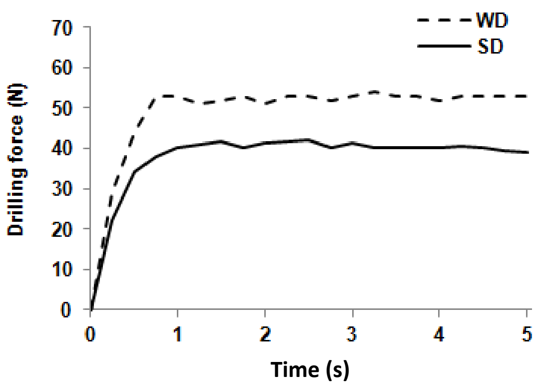

Figure 4. Evolution of thrust force in bone drilling using WD and SD (drilling speed – 1800 rpm, feed rate – 30 mm/min, drill size – 4.8 mm).

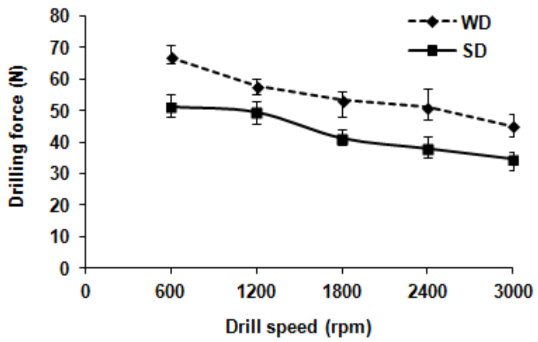

Figure 5. Effect of drill speed on thrust force (drill diameter – 4.8 mm, feed rate – 30 mm/min).

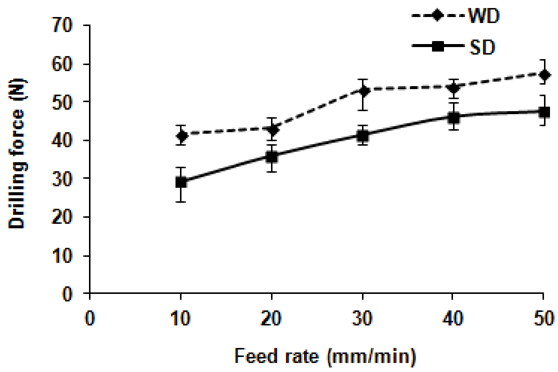

Figure 7. Effect of feed rate on thrust force (drill diameter – 4.8 mm, drill speed – 1800 rpm).

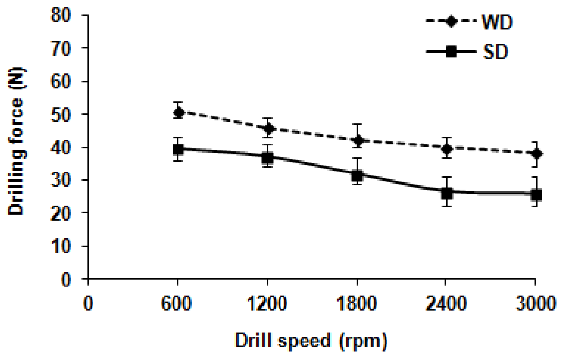

Figure 6. Effect of drill speed on thrust force (drill diameter – 2.5 mm, feed rate – 30 mm/min)

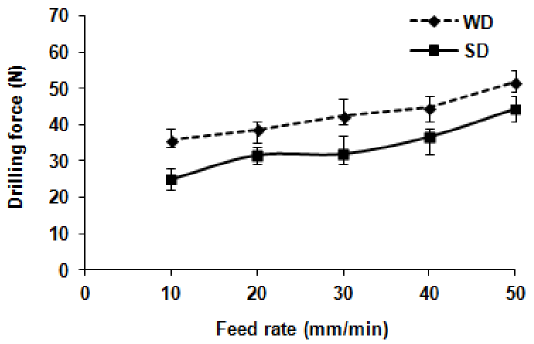

Figure 8. Effect of feed rate on thrust force (drill diameter – 2.5 mm, drill speed – 1800 rpm).

3.2. Effect of Feed Rate on Force

The effect of the feed rate on the drilling force using both types and size of drills was also studied. The drilling speed was kept constant at 1,800 rpm to find the effect of feed rate alone. The trend with which the force rose with an increase in feed rate was similar for both types of drills. The variation of force with feed rate for both types and sizes of drills is shown in Figs. 7 and 8. A linear increase in force was found with an increase in feed rate. The force was observed to increase by 39% (from an average maximum force of 41–57 N) when the feed rate was increased from 10 mm/min to 50 mm/min using a worn drill 4.8 mm in diameter (Fig. 7). Similarly, an increase of 62% (from an average maximum force of 29–47 N) was noted for a similar change in the feed rate when a sharp drill was used. The force dropped from 41 N to 29 N when the drill was changed from worn to sharp using a feed rate of 10 mm/min and a 4.8-mm drill (Fig. 7). At a higher feed rate of 50 mm/min for the same size drill, the force dropped by 10 N. A comparison of sharp and worn drills showed a similar trend when using a 2.5-mm-diameter drill (Fig. 8). A higher feed rate increased the chip cross-sectional area that in turn raised the cutting force. Thicker chips increased the resistance, which caused an increase in the cutting energy.

3.3. Effect of Drill Speed on Torque

The effect of drill quality and size on drilling torque was also studied using different spindle speeds. Figures 9 and 10 show the variation in torque with drill speed when a sharp and worn drill penetrated into bone. Similar to drilling force, torque dropped when the drill speed was increased. The drop in torque was similar for both types of drills. However, small variation between the torque measurements was observed between the sharp and worn drills for the same drilling speed. The slightly lower torque values obtained when using a worn drill may be due to the slip of the blunt edges of the drill on the bone in a tangential direction. Such

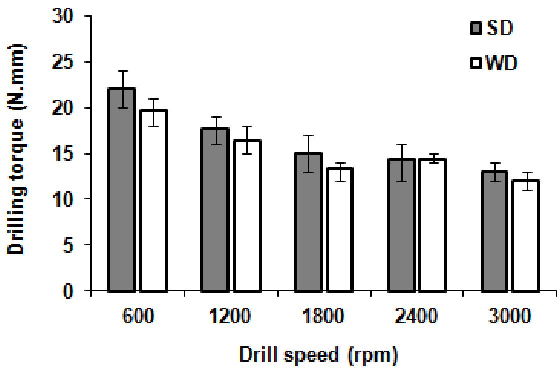

Figure 9. Variation of torque with drill speed (drill diameter – 4.8 mm, feed rate – 30 mm/min).

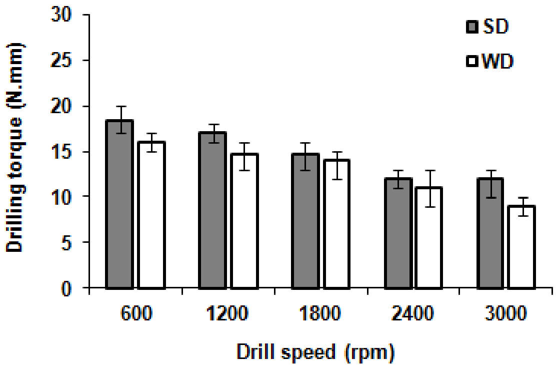

Figure 10. Variation of torque with drill speed (drill diameter – 2.5 mm, feed rate – 30 mm/min).

conditions did not generate enough tangential force compared with those produced in a sharp drill.

3.4. Statistical Analysis

A simple statistical analysis was performed to determine the effect of drill speed and feed rate on the level of drilling force and torque for both types and sizes of drills. The average drilling force measured with a worn drill was found to be larger than that measured with a sharp drill. The average drilling torque measured with sharp drill was found to be larger than that measured with a worn drill. Figures 11 and 12 show a comparison of drilling force and torque for both types and sizes of drills for different drilling conditions.

4. Discussion

The wear in drilling metals may significantly increase with an increase in the drilling thrust force and torque (El-Hofy 2013). As discussed earlier, in the present study, the thrust force gradually increased when the drill bit penetrated into the bone and dropped during the exit stage. The rise and drop in force was due to the engagement of the drill cutting edges with the bone during the penetration and exit stages. The decrease during the exit stage reduced the average thrust force over the drilling time. Large drilling force and torque may cause drill breakage during surgical incision (Jantunen 2002). This study demonstrated that using a worn drill would result in a greater chance of breakage due to the large drilling force inflicted as compared to a sharp drill. Different readings of force and torque obtained using the same drill size and type may be attributed to the anisotropic nature of bone, its mechanical properties, and differing bone porosity at different locations.

The velocity with which material is removed in the vicinity of a drill bit axis is small. In drilling, the chisel edge experiences an indentation process while the cutting lips perform orthogonal cutting (Galloway 1957). Modeling the forces experienced by the chisel edge is important since it significantly contributes to the overall thrust force experienced by the drill (Stephenson and Agapiou 1992). Several factors such as stiffness of the material being cut, feed rate, rotational speed, cutting fluids, drill size, drill geometry, and the friction between the drill and the workpiece material contribute to varying thrust force. The findings of this study are comparable to those reported in other empirical works (Alam *et al.* 2011b; Hillery and Shuaib 1999). The level of force was significantly reduced with an increase in the number of revolutions of the drill. A higher drilling speed produced a lower force due to the quick chip formation mechanism and the decrease in mean friction between the drills and the bone (Alam *et al.* 2011b). The decrease in drilling force with an increase in drilling speed was also observed in other studies performed on bovine cortical bone (Hillery and Shuaib 1999). In a recent study performed on porcine bone (Xu *et al.* 2014), the drilling force was found to decrease both with and without saline cooling. The obvious reason for an increase in drilling force with an increased feed rate was due to the increase in the material removal rate per revolution of the drill. Higher feed rates caused the average friction between the drill and the bone to rise, which increased pressure on the drill.

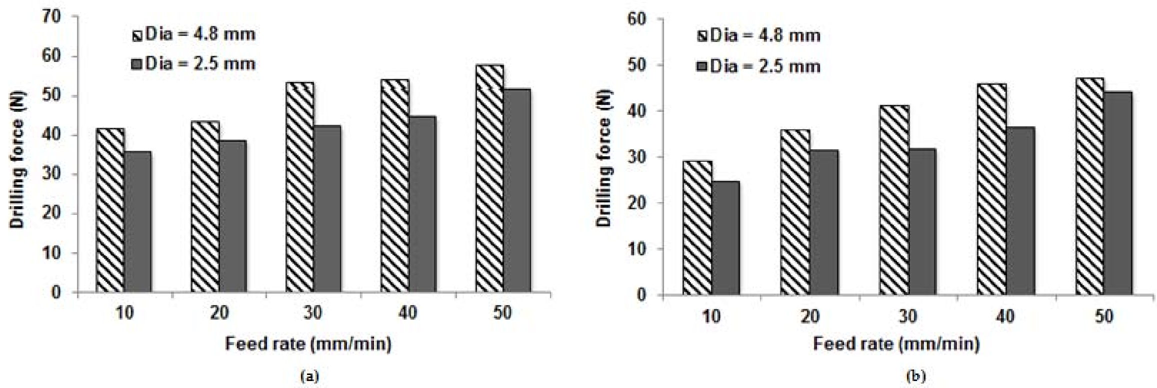

Figure 11. Variation of drilling force with feed rate for a constant speed of 18000 rpm. (a) WD, and (b) SD for different diameters of drills.

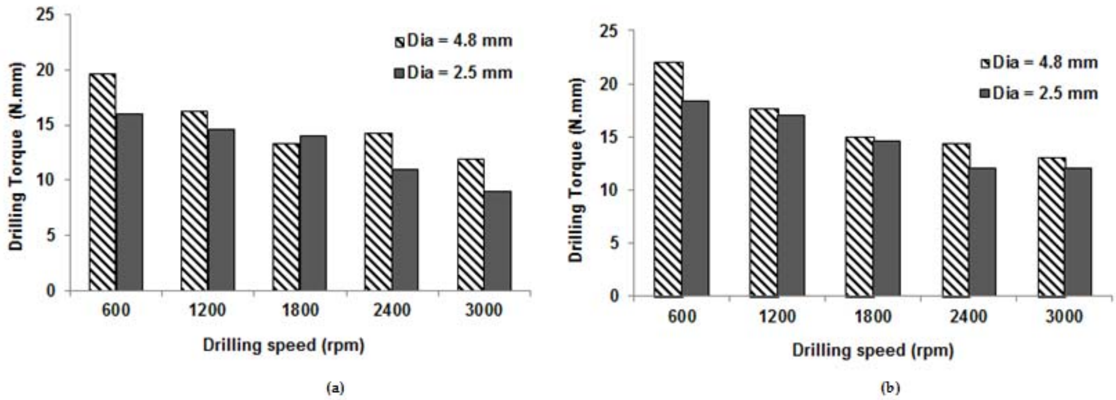

Figure 12. Variation of drilling torque with drilling speed for a constant feed rate of 30 mm/min. (a) WD, and (b) SD for different diameters of drills.

The results presented in the current study overlapped with another recent study (Lughmani *et al*. 2015).

The drilling force was also found to be strongly influenced by varying feed rates while simulating dry drilling using finite element analysis (Lughmani *et al.* 2013; Lughmani *et al*. 2015). Studies have found that maximum bone temperatures were strongly correlated to the drilling force (Abouzgia and Symington 1996; Bachus *et al*. 2000). The majority of previous studies found an increase in bone temperature that correlated with an increase in drilling speed (Abouzgia and Symington 1996; Bachus *et al*. 2000), with some exceptions which reported an inverse relationship between the drilling force and bone temperature (Abouzgia and Symington 1996). The conflicting results reported in the literature arise from the variety of test specimens and drilling conditions. Whether or not drilling force affects bone temperature, it is important to minimize pressure on the drill to avoid overstressing the bone tissue.

Surgeons and technicians in orthopedic surgical clinics have to discard drills when they become blunt. They discard the drills based on their experience and sense of penetration force. However, they do not have any experimental data on the level of force and torque caused by sharp and worn drills. Experimental data from the current study will provide scientific information to the medical community based on quantitative analysis of drilling force and torque. The results of this study should also contribute to the development of new surgical drills which will have force and torque sensation mechanisms. Such systems will signal the surgeon to discard the drill if the force and torque values reach a threshold level, therefore making bone drilling safer.

5. Limitations of this Study

This study did not measure the force and torque as a function of drilling depth. In the drilling process, the chips compact as the depth increases inside the flutes, thereby increasing the torque (Mellinger *et al*. 2002). The increase in the drilling depth generates improper conditions for the cooling fluid to access the cutting zone. Under these conditions, the drilling tools' wear increases, imparting more pressure on the drill in the cutting direction. The maximum speed used in this study was 3,000 rpm. Further studies are required to explore the effect of drilling speeds higher than those used in this study. Further research is required to relate the amount of the drill wear with the drilling force and torque. Geometries of drills other than those used in this study are required to be tested to obtain more generalized data on bone drilling. In this study, drilling tests are performed on hard cortical bone only. Depending on the fracture site, the drill may be used to produce holes in spongy bone (trabecular bone). Further research is suggested to investigate the effect of drill quality on thrust force in drilling spongy bone under various drilling conditions. Further studies are required to check the quality of the hole surface using both types of drills and its effect on bone regeneration. New techniques are required to check real time wear of the tool based on cutting force and torque measurements.

6. Conclusion

In this article, the drilling thrust force and torque produced during the drilling process was measured and compared using sharp and worn surgical drills. The effect of drilling speed and feed rate on the thrust force was investigated in the presence of cooling with water. The main aim of this research study was to provide engineering-based information to surgeons and technicians about the force required by them to push drill into bone. Experimental results demonstrated a lower drilling force using a sharp drill compared to a worn drill for similar drilling conditions. The thrust force may be reduced using a combination of low speed of penetration and higher drill rotation speed. The torque may be lowered by using a higher drill rotational speed.

The thrust force must be kept at minimum to avoid mechanical and thermal damage to the bone tissue. It is hoped that the results of this research will be useful for surgeons to understand the effect of drill wear on the outcomes of the drilling process. The data obtained from this study may be useful for the improvement of automatic bone surgical drilling machines and the optimization of bone cutting procedures.

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