Smart Bone Drilling Machine

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***Abstract*—Bone drilling operations are carried out in hospitals in different surgical operations worldwide. Such procedures are carried out by using a manual bone drill which is operated by the surgeon. This operation is very delicate, precise and requires high accuracy to drill until the specified depth is reached. This paper present a smart mechatronic tool for automatic bone drilling, where the linear movement and rotation of the drill bit are controlled. Breakthrough detection method and control algorithms are implemented to stop the drilling procedure upon penetration of bone. Finally, validation and testing of the prototype have been carried out.**

***Index Terms*—assisted surgery, bone drilling, breakthrough, layer detection**

I. Introduction

Bone drilling is an important process which is frequently encountered in various medical practices. In bone drilling, a drill is used to make a hole through the bone that will be used for the insertion of screws for fixing fractured bone parts.

Bone drilling operations are carried out in hospitals in different surgical operations worldwide. Currently, the drilling procedures are carried out by using a manual bone drill which is operated by the surgeon. This operation is very delicate, precise and requires high accuracy to drill until the specified depth is reached. Any minor deviations in the drilling path can cause further complications which may include damage to the tissue around the bone.

Bone consists of two types of tissues which are: Cortical bone (hard tissue) and Cancellous bone (soft tissue). By estimating the density of the soft and hard tissues, the surgeon is then able to determine how much force and drilling speed the drilling process should requires.

Due to the high level of precision needed during drilling operations, a real need for an automatic bone drilling device is necessary. Two important characteristics for this device should be considered; the first is the automatic detection of the drill bit having penetrated the bone. The second important characteristic of the design is the ability to drill in a perfectly straight line without deviating. By implementing these features in the automatic bone drill, the damage to the tissue surrounding the bone can be minimised.

For the last decade, many design solutions have been proposed in order to improve the current drilling procedure and the breakthrough detection technique in bone drilling operations. A review of some mechatronic bone drilling methodologies found in the literature is provided in this paper.

Development in the drilling tool have led to many semiautomatic and automatic systems that make use of:

1) Predefined depth values [1].

2) Control algorithms that uses various advanced sensors to acquire measurement while they are attached to the drill bit and other parts of the drilling machine [2, 3]

In general, the drilling penetrating force and cutting torque are the two parameters that most of the current control methods are based on for detecting drill bit breakthrough. These parameters are measured by attaching sensors onto the drill tool.

Allota B et al. [4] presented a technique for detection of breakthrough imposing an upper threshold to the first derivative of the penetrating force. This method could only be done by obtaining the values of the penetrating force and the cutting torque first.

Ong and Bouzza-Marouf [5] presented a technique for detection of the drill bit breakthrough where they focused on studying the fluctuations in the penetrating force profiles. Therefore, they were able to convert the rotation speed of the drill bit into more consistent profiles where it helped in the detection of drill bit breakthrough.

One of the method of breakthrough detection was also presented by using a fuzzy control logic to identify four stages [6]. Those stages are

1) Start of bone drilling.
2) Stabilization of drilling.
3) Start of protrusion.
4) Point of complete breakthrough.

The transition from one stage to the other is held at a specific drilling point which will allow the drilling procedure to be controlled. The transition between four stages in this method is based on a specific bone type and thickness, which means this method will lack precision and accuracy if the bone type and thickness is to be changed.

Colla and Allota [7] presented a breakthrough detection method that make use of wavelets. Their work investigated a mechatronic drill for use in orthopedic surgery, where the controller for the drill is based on wavelet. Wavelet analysis of the thrust force signal was simulated and used to generate the penetration speed of the drill.

B. Allotta et al [8] presented a technique for breakthrough detection based on neural networks and fuzzy logic. The drilling tool presented is a hand-held bone drilling tool which make use of a fuzzy logic controller to detect the breakthrough point by controlling the penetration velocity.

Manuscript received August 14, 2018; revised September 7, 2019.

doi: 10.18178/ijmerr.9.2.248-251

I. Díaz et al. [9] conducted an experiment to test Ong and Bouzza-Marouf detection breakthrough method [5]. Two main issues were detected in the detection method which are a marginally large delay in the breakthrough detection point and several false detection point. It was found that those two issues presence is due to having a fixed threshold value. Therefore, each time the force signal passes through the threshold value a false detection point is sensed.

Another approach for detection breakthrough of drill-bit found in the literature is based on position measurement of the drilling tool. This method makes use of the error signal between the actual position of the drilling tool (using an encoder) and a reference signal (a pre-defined linear signal). During the drilling procedure, the error signal is increases due to the stiffness of the bone. A control algorithm was used to detect an immediate incline in the error signal and stop the drilling procedure. [9]

The work in this paper presents a mechatronics device for automatic bone drilling where the linear movement and the rotation of the drill bit are automatic and controlled. The proposed system carries out the drilling procedure after having being placed in the desired position for the hole to be made. The drilling procedure will then take place automatically following pushing start button. A control algorithm should be able to stop the drilling procedure at bone breakthrough.

This paper proposes and validates a new drilling methodology that could contribute to the current body of knowledge related to automatic bone drilling. The main objective is to present a mechatronic tool that is able to carry out a full automatic drilling procedure while controlling the rotation and the axial movement of the drilling tool. Finally, a prototype of a mechatronic bone drilling system that is able to implement the proposed breakthrough detection method is presented.

II. Description of the Proposed Bone Drilling Methodology

In this section, the procedure taken in developing the final design will be discussed in relation with two aspects which are: mechanical design and control unit.

A. Design of the Device

Mechanical design consists of a ball screw linear actuation mechanism, drill motor holder and brackets and bearings. Control unit which consists of a control box, including the sensors used, motor controllers and micro-controller.

Ball bearing are used in order to achieve the linear rotational movement of the ball screw while minimizing frictional loses and increasing the ability of handling the stress [10].This proposed design make use of ball screw linear actuating as a drilling guide, this has advantageous over other types of linear actuation methods Such as precise positioning and high accuracy. Therefore, the ball screw actuators are used high precision and accuracy are required.

Fig. 1 shows the mechanical structure of the proposed bone drill before the 3D printing takes place. This had to be done to test the strength and durability of the components in order to undertake the drilling operation. Two main parts can be identified in the proposed bone drill device:

1) Feeding mechanism: The mechanism responsible for driving the motor and the drill bit in the axial direction.

2) Motor and drill bit set which is used for the drilling procedure.

The feeding mechanism is responsible for the driving the motor and the drill bit in the axial direction consists of: RS Pro DC Geared Brushed motor (321-3158, 4.5 - 12v DC) and a ball screw. The motor responsible for carrying the drilling procedure is RS Pro DC motor (321-3192, 12 v DC) that gets con-trolled by a micro controller to drive the motor at the de-sired speed. The mechanical components of the bone drilling device are designed on Auto-CAD inventor and simulated using finite element analysis to insure the ability of the parts to handle the forces and stresses that arises from the drilling procedure. Then the parts were 3D printed and used in the assembly of the system.

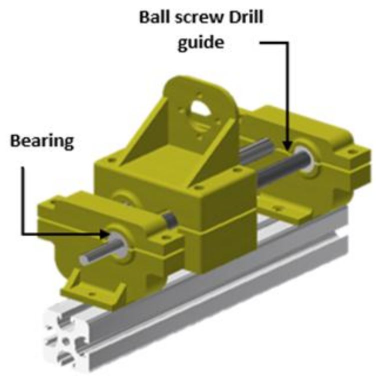

Figure 1. Bone drill structure computer model

B. Control Unit

The control unit for the proposed system consists of the microcontroller, motor drivers, current sensor and extra electronic components necessary for the execution of the procedure in a successful manner. The system is to be positioned manually where the hole is desired and the start button is pushed. The drilling procedure then commences until breakthrough is detected. Following that, the system stops and retract to its initial position.

The detection breakthrough method used for the proposed system makes use of the current drawn from the drilling motor. This method is considered simple as it is effective, with more resistance faced during the drilling the more current is withdrawn from the motor.

In electric motors, when an unloaded DC motor spins, a backward flowing electromotive force is generated to resist the current being supplied to the motor. As the rotational speed increases, the current through the motor drops. However, when a load is applied to the motor, the rotor slows down leading to an increase in the current draw through the motor.

The current is proportional to the torque. Therefore, if there is increase in the mechanical load (resistance), the more mechanical power is required as per equation (1):

$$P = V * I. \quad (1)$$

A current sensor impeded in the drilling motor controller is used to measure the current needed from the drilling motor to overcome the resistance faced through the drilling procedure. The following is discovered, the presence of few spikes once the start button is pressed and the motor starts running which is called the starting current. Once the drilling procedure takes place, the current sensed from the drilling motor starts to increase due to the increase in resistance (stiffness of the bone) till breakthrough occurs. This happens at the peak of the signal where the measured is at its highest.

Fig. 2 Shows a demonstration for the current sensor readings while drilling (free rotation) and stalling the motor (manually added resistance) to observe the increase in current due to the increase in resistance.

The vertical axis values in Fig. 2 represent the current sensor readings and the horizontal axis represent the time (s). This figure proves the presence of spikes in the current sensor reading while stalling the motor is clear and far from the reading of the starting current or the current withdrawn during free rotation. Therefore, this method can be used for detecting the moment at which breakthrough occurs (by having the highest peak above a certain threshold).

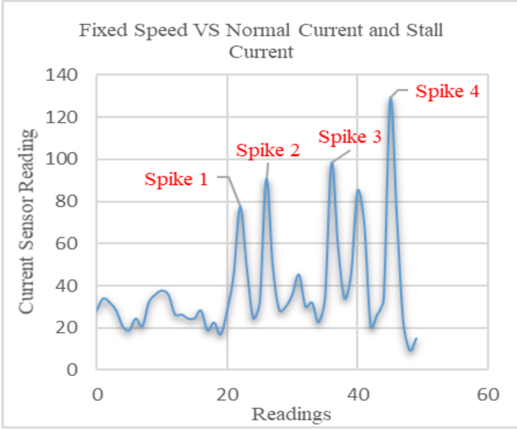

Figure 2. Bone drill structure computer model

III. EXPERIMENTS AND RESULTS

This section focuses on validating and testing the proposed mechatronic bone drilling system. The setup for the undertaking of the experiments consists of the following: porotype of the proposed bone drilling device and a vice for holding the bone. This configuration can be seen in Fig. 3.

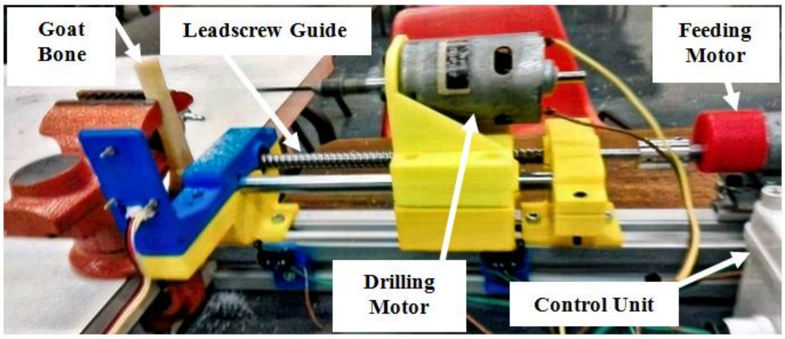

Figure 3. Smart bone drilling device prototype.

Several drilling experiments were conducted on goat bone while varying the feed rate and the drilling speed. The input feed rate was varied from 3 to 12 mm/s and the drilling speed was varied in the range of 2500 to 7500 rpm with incremental intervals of 2500 rpm.

The bone used during the drilling procedure was first added in boiling water to get rid of any fat or meat that is attached to the surface of the bone and then fixed using the vice, those two aforementioned points are considered limitations which is a scenario that will not exist in real drilling procedures. These limitations will not allow the experiments to correlate to actual bone drilling procedures. However, it can prove the working principle of the breakthrough detection method proposed in this paper. [4, 5, 10]

Fig. 4 shows the results of the current sensor reading when drilling into goat bone. The feed rate was set to 4.8 mm/s and the rotational speed was set to 2500 rev/min, an actual spike can be seen in the sensor signal which correlates to breakthrough of the drill bit.

Fig. 5 shows the moment of protrusion of the goat bone. At that exact instant, the system came to a complete stop and reversed back to its initial position.

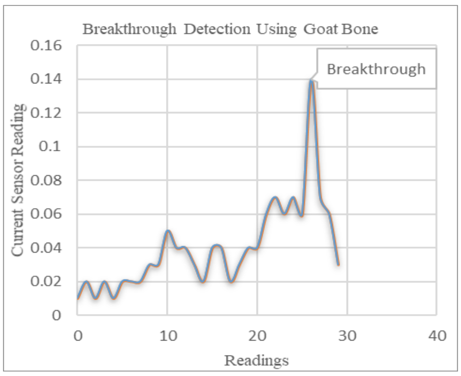

Figure 4. Breakthrough detection while drilling in goat bone.

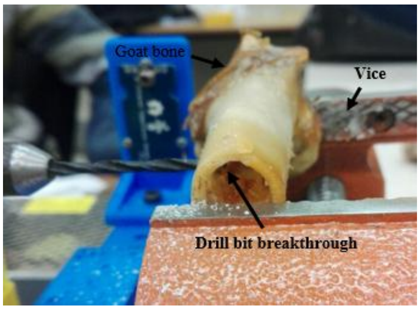

Figure 5. Moment of drill bit breakthrough.

TABLE I. CURRENT SENSOR READING AT BREAKTHROUGH POINT FOR DIFFERENT BONES

Bone type	Thickness [mm]	Current sensor reading at break-through
Goat	3	0.07
Goat	3.5	0.14
Cow	5.86	0.162

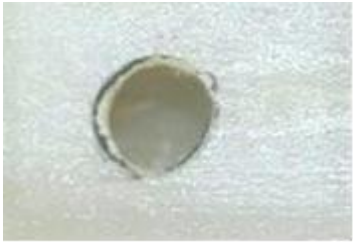

Figure 6. Drilled hole.

Table I shows the value of the current sensor readings measured at moment of breakthrough. Those values were used later on to program the microcontroller in order to successfully detect the breakthrough point for similar type of bones with the same thickness.

Fig. 6 shows the result of the drilling procedure for a goat bone of thickness equals to 3.5 mm. the uniformly of the drilled hole and the stability of the drill bit can also be seen on the outer surface of the hole.

The current values obtained from the test run for the breakthrough were used as a threshold value. Where for a 3 mm goat bone, the drilling tool breakthrough occurs at a current sensor reading of 0.07. This concept was used to program the microcontroller to stop the drilling procedure if the threshold value is reached and there is a sudden incline in the slope of the current sensor signal. Both those conditions combined has led to a successful automatic drilling procedure while stopping at bone breakthrough.

IV. CONCLUSION

This paper proposed and presented a mechatronics tool for automatic bone drilling. The system was able to carry out the drilling procedure with stability and accuracy while stopping drilling upon breakthrough detection.

This system makes use of a test run to determine the range of current sensor values that correlates to the drill bit breakthrough. These values are then used to program the microcontroller for successful breakthrough detection in any drilling procedure for the same type of bone with the same thickness.

Improving the prototype design is necessary in future work in order to meet the real requirement for bone drilling operation and to achieve the optimal technique for bone drilling while adhering to the safety roles.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGMENT

We would like to acknowledge the support of the Mechatronics Department of Nelson Mandela University for the Financial Support provided.

REFERENCES

[1] W. Anderson, "Depth controllable and measurable medical driver devices and methods of use," ed: Google Patents, 2018.
[2] B. Allotta, "Surgical drill with bit penetration control and breakthrough detection," ed: Google Patents, 2000.
[3] A. Carl, J. Adams, K. Craig, D. Lavery, G. Fischer, S. Anthony, et al., "Methods and systems for controlling the operation of a tool," ed: Google Patents, 2005.
[4] B. Allotta, F. Belmonte, L. Bosio, and P. Dario, "Study on a mechatronic tool for drilling in the osteosynthesis of long bones: tool/bone interaction, modeling and experiments," *Mechatronics*, vol. 6, pp. 447-459, 1996.
[5] F. R. Ong and K. Bouazza-Marouf, "Drilling of bone: a robust automatic method for the detection of drill bit break-through," in *Proc. the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, vol. 212, pp. 209-221, 1998.
[6] V. Kaburlasos, "Automatic detection of bone breakthrough in orthopedics by fuzzy lattice reasoning (FLR): the case of drilling in the osteosynthesis of long bones," in *Proc. the Mechatronical Computer Systems for Perception and Action (MCPA97)*, pp. 33-40, 1997.
[7] V. Colla and B. Allotta, "Wavelet-based control of penetration in a mechatronic drill for orthopaedic surgery," in *Proc. 1998 IEEE International Conference on Robotics and Automation*, 1998, pp. 711-716.
[8] B. Allotta, G. Giacalone, and L. Rinaldi, "A hand-held drilling tool for orthopedic surgery," *IEEE/ASME Transactions on Mechatronics*, vol. 2, pp. 218-229, 1997.
[9] I. D áz, J. J. Gil, and M. Louredo, "Bone drilling methodology and tool based on position measurements," *Computer Methods and Programs in Biomedicine*, vol. 112, pp. 284-292, 2013.
[10] T. McNier, J. G. Johnson, and P. Engineer, "Specifying, selecting and applying linear ball screw drives," *Thomson Industries*, Inc, Wood Dale, 2016.

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