

Bone Drilling Breakthrough Detection via Energy-based Signal

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Abstract— Bone drilling is performed in many surgeries and is considered as one of the principal treatments of bone fracture. Despite being a common practice, it would cause damage to the delicate surrounding tissue if the process is not well controlled. Therefore, monitoring and control of the drilling process is crucial, yet challenging to avoid damage to the delicate. One main concern is to detect drill bit breakthrough automatically. In this paper, a new energy-based parameter, removal energy density, is proposed as detecting signal to determine the breakthrough instance in bone drilling. This signal profile would not vary much under different drilling parameters, hence reducing the difficulty in setting threshold for detection. Real world experiment on porcine bone is performed and verifies the proposed method.

I. INTRODUCTION

Bone drilling is a common procedure in many surgical interventions such as orthopedics, dentistry, otology, spine and maxillofacial surgery. As one of the principal methods of bone fracture treatment, bone drilling produces holes in the bone for screws insertion to serve as the internal fixation of fractured parts for stabilization. In the bone drilling procedure, surgeons operate drilling tools manually to make a hole in the bone and remove the material from it for screw insertion.

Despite the common usage of bone drilling, it can lead to two major potential damages. First, the thermal energy generated by drilling can cause thermal necrosis, i.e. killing tissues and bone cells. Second, if the drill bit does not stop right at the breakthrough point, the delicate tissue nearby can get damaged due to the inertia of the drilling thrust force. Therefore monitoring and controlling the bone drilling process is of paramount importance to minimize damage to body, where the ability to detect the moment of breakthrough plays a significant role.

Currently in practice, the surgeons perform the drilling manually, relying on the experience and intuition. And when drilling in critical area, the surgeons use x-ray to scan the target area at regular time interval to determine the penetration depth and the safety region where the drill bit has already breakthrough. This approach is the safest but also the most demanding for both time and manual effort.

At the same time, different approaches have been proposed to solve the breakthrough detection problem. Most of the

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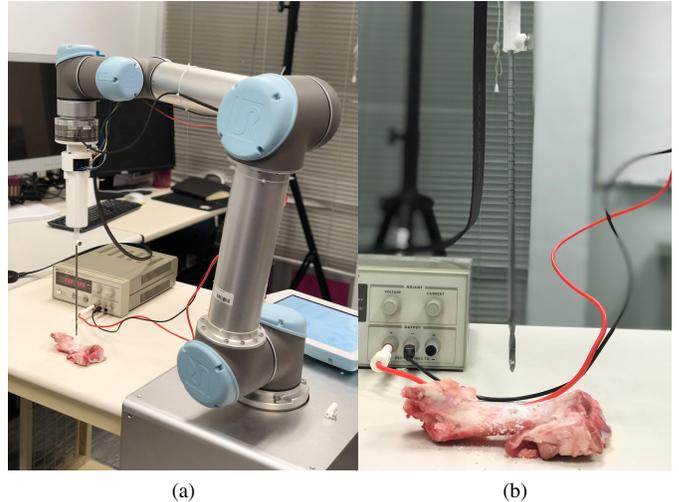


Fig. 1: The experiment setup. (a) The experiment was conducted with UR5 robot arm equipped with an electronic drill. (b) The porcine bone was utilized to perform the drilling procedure on.

works [3] [4] [6] [7] [8] rely on thresholding the thrust force signal in drilling to determine the breakthrough instance.

In contrast to the previous works, a novel breakthrough detection method is proposed and analyzed in this paper. A new parameter, removal energy density e_b , is derived and utilized to detect breakthrough and our method has been verified by several experiments performed on porcine bone (shown in Fig.1).

II. RELATED WORK

In previous works, several approaches for bone drilling breakthrough detecting were proposed. Diaz [1] and Accini [2] used the position error between the command and real position to detect the acceleration when the drill is about to protrude, and used threshold of error derivative as detecting signal. Lee [3] [4] used the sharp edge of thrust force signal and the trend of both drilling torque and feed rate, which represent whether the signal has been continuously increasing or decreasing for a period of time. Colla [5] described a 3 tree-structured wavelet decomposition of thrust force signal, transforming into 3 different coefficients. The system then tracks the abrupt changes in the 3 coefficients during breakthrough. Allotta [6] built a theoretical model of thrust force and torque response during the drilling process,

which is used to set the threshold for the force signal to detect the breakthrough. Brett [7] used the increment in force and decrement in torque over n sample period for detection. Ong [8] used a modified Kalman filter over the force difference between successive samples and detected the sharp drop in the filtered signal. Hu [9] used a recognition function of force signal and detected the abrupt change in the function signal at transition layer. Hsu [10] developed a modular system that is compatible with any motor driven drills. The system senses the current consumed by the drill DC motor as there is a direct relationship between current and cutting torque, then a preset threshold is used to detect the rapid drop of the signal. Laburlaso [11] used classification, feature extraction and learning method to extract the mapping among torque, force and the bone thickness. In his work, a two-layer fuzzy lattice was used to train on force and torque data to estimate bone thickness. Kim [12] incorporated photoacoustic imaging into the detection. He integrated an ultrasound probe into the system to sense blood vessels behind the bone in order to determine the safe region for drilling.

III. BREAKTHROUGH DETECTION ALGORITHM

A. Basic Idea

Drilling is a coupled problem as the rotational and the translational information is interrelated. As described in [6] [8] [10], when drilling, changing the rotational parameters, e.g. the rotational speed, will affect the translational behaviours, like thrust force and feed rate. Therefore in the drilling process, both rotational and translational information should be considered to give an accurate detection of breakthrough. However, when tackling the breakthrough detection problem, most of the previous works only consider one side of the information, such as the feed rate, thrust force profile [5] [6] [8] [9], or torque profile [7] [10]. Though there are few works considering both information, their algorithms are designed in a heuristic way, for example breakthrough is determined only when the torque signal keeps increasing and the force signal continues to be decreasing at the same time [3] [4] [7].

Therefore the detecting signal in previous works does not provide much insight to the surgeon on the way to determine the breakthrough point based on the signal, i.e. how to set the threshold for the detection. Most of the works set the threshold through calibration on several specimen samples with a specific drilling parameter. If the drilling parameters change, new calibration is needed. Hence deciding the threshold for detection becomes a challenging task as there are many other factors need to be considered.

In light of this, this paper aims to give a parameter that depends only on the bone properties, i.e. the signal profile remains the same as long as the material being drilled is the same even under different drilling parameters. We proposed a new parameter, bone removal energy density e_b , which is the energy required to remove a unit volume of bone during the drilling process, as a detecting signal for breakthrough detection.

B. Methodology

To determine the removal energy, the conversion of energy during the the drilling process is analyzed. During the process, energy is applied through the drill motor to the system, and the energy is consumed to remove the bone, and heat and sound energy is also released. Assuming the sound energy is negligible, we now consider the conversion and conservation of energy among the energy applied by the drill motor to the bone E_{drill} , the energy consumed to remove the bone E_{Bone} , and the heat energy released during the process E_{heat} .

First, the work done by the drill motor to the bone E_{drill} denotes the work done due to the drilling torque acting on the bone:

$$E_{drill} = \int \tau d\theta \quad (1)$$

where the drilling torque τ equals to the resistance torque from the bone τ_{resist} and θ represents the angle rotated.

Second, the removal energy of the bone E_{Bone} is strongly correlated to the bone property [13], i.e. bone density and bone strength, the denser or the higher strength the bone is, the more energy is required to remove the bone. Therefore, we define a removal energy density e_b such that the removal energy of bone E_{Bone} can be represented by:

$$E_{Bone} = \int_V e_b dV \quad (2)$$

where V is the volume of bone being removed at the time instant.

Third, for the heat generated, there are two major sources of this thermal energy E_{heat} . One of the source is from the plastic deformation and shear failure of bone which is used to remove the bone, while the other one is due to the friction of the drill bit and the bone machining surface which does not involve in bone removal [14] [15]. If the drill bit is sharp, the friction between drill bit and bone can be neglected [14]. As this would be the situation in the surgical procedure, therefore it can be assumed that all the thermal energy comes from the deformation and shear failure of bone which equals the removal energy of the bone. In the whole process, the applied drilling energy is consumed to remove the bone and is then converted to and released as heat. Therefore, the drilling energy E_{drill} equals to the removal energy of the bone E_{Bone} :

$$E_{drill} = E_{Bone} \quad (3)$$

Substituting Eq. (2) and $dV = \dot{V} dt$ into the Eq. (3) yields:

$$E_{drill} = \int_V e_b \dot{V} dt \quad (4)$$

Since e_b is a function of bone property, then taking time derivative on both side yields:

$$\frac{dE_{drill}}{dt} = e_b \dot{V} \quad (5)$$

Noting that \dot{V} is the bone removal rate which equals $\dot{V} = \pi r^2 \dot{d}$, the equation now becomes:

$$\tau_{resist} \dot{\theta} = e_b \pi r^2 \dot{d} \quad (6)$$

where $\dot{\theta}$ is the drilling speed of drill bit, r is the drill bit radius, \dot{d} is the feed rate of the drill, and e_b is the bone removal energy density, which is a function of the bone properties of the bone being drilled at the drill bit.

Using Eq. (6), the relationship of e_b with other drilling parameters, $\dot{\theta}$, \dot{d} and r , are established, and e_b can be estimated given all other variables, which can be measured through different sensors.

As the strength and density of the nearby tissue is much lower than that of the bone, by monitoring e_b , drill bit breakthrough point can be detected, as indicated by a sharp drop in e_b . Detailed experiment results are discussed in Section V.

IV. IMPLEMENTATION

A. Hardware Setup

A robotic drill is built and attached to a UR5 robot arm, as shown in Fig. 1, to test the proposed method for breakthrough detection. To evaluate the proposed method, porcine bones are used as specimen to be drilled on. The target porcine bone was placed and fixed on the experiment platform while the drill is adjusted to align perpendicularly to the platform.

As mentioned in Eq. (6), the feed rate \dot{d} , drilling speed $\dot{\theta}$, resisting torque from bone τ_{resist} and the drill bit radius r are needed for the estimation of e_b . The UR5 arm manipulator is used to provide the feed action and thrust force, the UR5 pendant is used to control the feed motion of the drill manually during the drilling process while the velocity information of the tool, i.e. actual feed rate of drill \dot{d} , can be calculated through the joint position and velocity feedback of the robot.

Besides, an optical rotary encoder is installed to the drill motor to provide the drilling speed $\dot{\theta}$ information. As for the resisting torque from bone τ_{resist} , the drill motor dynamic as shown in Eq. (7) is used to calculate τ_{resist} .

$$J\ddot{\theta} + b\dot{\theta} + \tau_{resist} = k_m I \quad (7)$$

where J , b and k_m is the inertia, friction and motor torque constant of the motor respectively.

Thus, a current sensor is installed on the drilling motor and $\ddot{\theta}$ is calculated by numerically differentiating $\dot{\theta}$ measured by the optical rotary encoder. Calibration is needed before using the dynamic to calculate τ_{resist} . Standard Recursive Least Square is adopted to identify J and b as they are assumed to be constant. The calibration can be performed easily by inputting a sine wave of drill speed to the system and not touching the drill for a few seconds such that the dynamic becomes $J\ddot{\theta} + b\dot{\theta} = k_m I$, then J and b can be calculated with the sensor data.

B. Estimation of e_b

In bone drilling, a dynamic parameter identification algorithm, i.e. Recursive Least Square with forgetting factor (RLS with forgetting factor), is adopted to estimate e_b .

RLS with forgetting factor has the ability to identify time-changing signal as a forgetting factor is added to the past

data. Detail of RLS with forgetting factor algorithm is as follow:

Given the regressive form:

$$y(t) = \phi^T(t)x(t)$$

We can estimate x through the RLS with forgetting factor algorithm as follow:

$$\epsilon(t) = y(t) - \phi^T(t)\tilde{\theta}(t-1) \quad (8)$$

$$P(t) = \frac{1}{\lambda} \left[P(t-1) - \frac{P(t-1)\phi(t)\phi^T(t)P(t-1)}{\lambda + \phi^T(t)P(t-1)\phi(t)} \right] \quad (9)$$

$$K = P(t)\phi(t) \quad (10)$$

$$\tilde{\theta}(t) = \tilde{\theta}(t-1) + K\epsilon(t) \quad (11)$$

We formulates Eq. (6) into the regressive form: $y = \tau$, $\phi = \pi r^2 \frac{\dot{d}}{\dot{\theta}}$, $x = e_b$ such that $y = \phi^T x$, and setting $\lambda = 0.9$. Using the RLS with forgetting factor, e_b can be estimated online and used to detect drill bit breakthrough through the sharp drop in e_b .

V. EXPERIMENTAL RESULT

A. Experimental Setup

An experiment is carried out to verify the feasibility of utilizing the proposed detecting signal for breakthrough detection. In the experiment porcine bones are drilled through using different drilling speeds and the feed rate is controlled manually through the pendant. Since the actual feed rate contains a lot of noise due to the vibration when drilling, e_b is only updated when the actual feed rate is larger than $5 \times 10^{-2} mms^{-1}$, such that the update and estimation of e_b becomes more stable. The result is reported in the following section.

B. Experimental Result

The e_b signals retrieved from each test is shown in Fig. 2. From the result, it can be seen that although different drill speeds are applied, the resultant e_b remains within similar range i.e. and shape, which verifies the theory of the proposed signal. And the variation of e_b in different test is due to the variation of bone properties in the drilling parts.

As shown in fig. 2, at the breakthrough point represented by the red dotted line, the e_b signal drops significantly. Therefore, by monitoring e_b , the breakthrough point can be detected accurately.

As most of the previous works are based on the force signal, the force profiles of the drilling tests are measured with a force/torque sensor so as to make a fair comparison with the proposed method. Sometimes the force signal variation is not strong enough to be detected, and the range of force signal differs when the drilling parameter is changed. These two factors lead to difficulties in setting the threshold and might cause a false or miss detection, causing damage to the patient. In contrast, the proposed signal e_b variation is strong at the breakthrough point as long as the removal energy of the two layers is not similar, as shown in the result. Second, the signal is in the same range even if the parameter is changed, such that threshold needs not to be calibrate or reset when the parameter is changed.

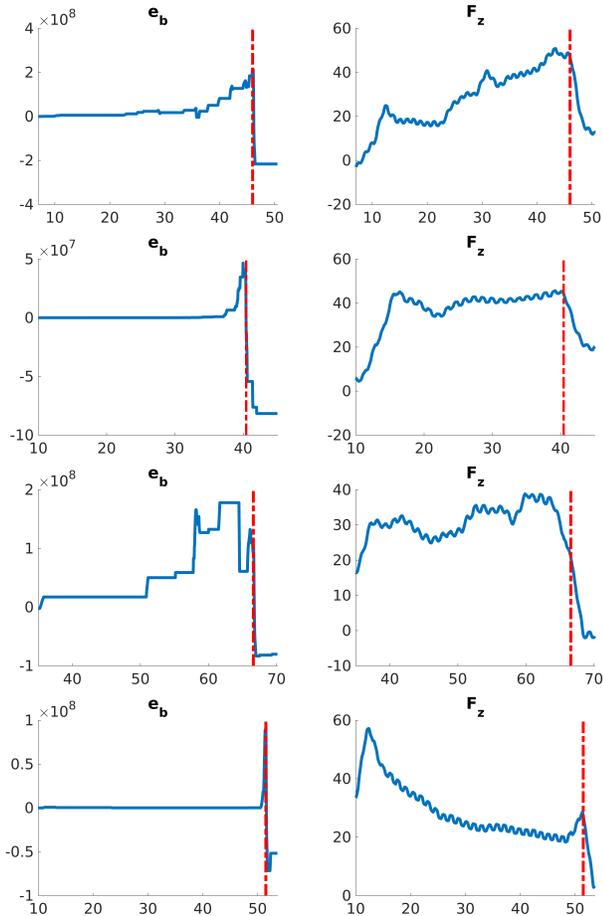


Fig. 2: The experiment result. The first column shows the result of removal energy density signal e_b and the second column represents the filtered force profile under the same condition. The red dotted line represents the breakthrough point instance. The radius of our drill bit is 2.2mm . The drill speeds are 300rpm , 350rpm , 400rpm , 450rpm for each row.

VI. CONCLUSION

As drilling is a very common procedure in surgery, and minimizing damage to patient is the most important issue to be considered during surgery, building an intelligent bone drilling system to reduce necrosis to nearby tissue is of a great interest. The main key feature of such system is the ability to identify the drill bit breakthrough point.

The previous works trying to solve the breakthrough detection problem still pose several limitation and challenges. One major challenge is how to decide the threshold of the detecting signal as the detection since the detecting signal profile, i.e. force signal profile in most of the previous works, changes under different drilling parameter.

The proposed drilling methodology adopted an energy-based approach to solve the breakthrough detection problem which incorporate both rotational and linear information of the drill bit, unlike previous methods that only consider rotational or linear information. The proposed energy-based signal e_b only depends on the bone properties, therefore

varying drilling parameters will not affect the signal, hence reducing the difficulties in setting the threshold of the detecting signal.

In the current study, a preliminary robotic drilling system is developed to study and test the proposed methodology. From the experiment, the removal energy density signal e_b drops sharply at the breakthrough instance, hence verified the feasibility to use e_b to detect breakthrough point.

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