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Using an admittance algorithm for bone drilling procedures

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ABSTRACT

Bone drilling is a common procedure in many types of surgeries, including orthopedic, neurological and otologic surgeries. Several technologies and control algorithms have been developed to help the surgeon automatically stop the drill before it goes through the boundary of the tissue being drilled. However, most of them rely on thrust force and cutting torque to detect bone layer transitions which has many drawbacks that affect the reliability of the process. This paper describes in detail a bone-drilling algorithm based only on the position control of the drill bit that overcomes such problems and presents additional advantages. The implication of each component of the algorithm in the drilling procedure is analyzed and the efficacy of the algorithm is experimentally validated with two types of bones.

1. Introduction

Drilling is a common procedure in bone surgery. It is used in orthopedic surgeries for fractures and bone reconstruction [1]; in neurological surgeries, for example in craniotomy and stereotactic surgery [2]; in ear surgeries, such as a cochleostomy for cochlear implantation [3] and in any otologic surgery [4]. In orthopedic surgeries, drilling is required in about 95% of post-trauma treatments and interventions, where holes are required to mount the screws needed to fix and correct bone fractures or to attach plates or other prosthetics.

Surgeons work very carefully, trying to control the penetration of the drill and avoid harming vessels and tissues located in the proximities of the bone. One of the main risks consists of projecting the drill bit beyond the structure being drilled. The safety of the patients relies on the experience of the surgeon, but it has been shown in experimental studies that surgeons drill beyond the far cortex by an average of 6.33 mm, depending on their age and experience [5].

Several technologies, each with different control algorithms and strategies, have been developed to help the surgeon to automatically stop the drill before it goes through the boundaries of the tissue being drilled. Most of them, implement algorithms and sensors to control the force of penetration and the torque of the drill.

In previous work we presented DRIBON [6,7], a new automated-mechatronic drilling system which implemented an algorithm based on the position control of the drill bit. This strategy is completely different from the rest of the technologies found in the literature. The aim of this work is to describe in detail the differences between our approach and related work (Sections 2 and 3), analyze in detail the implemented methodology (Section 4), and show its effectiveness when drilling different types of bones (Section 5). The distinguishing feature of the approach is that it allows drilling in different bone types without changing the control algorithm

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or building a neural network based on experimental data. Additionally, layer transitions can be properly detected before bone breakthrough.

2. Related work

This section presents a review of bone drilling methods and systems. They are grouped into categories depending on the strategy used to detect bone layer transitions.

2.1. Methodologies based on strong signal variation

One of the first methods in this group was presented by Brett et al. in 1995 [8]. They observed that the persistence presented in the increase of the torque and the decrease of the force at the moment of protrusion can be used to determine the exact moment at which to stop the drill. Their method determined that a change of layer occurs when threshold values in the increase of the cutting torque and decrease of the penetration force were reached.

In 1996, Allotta et al. [9] presented a new study focused only on a threshold value of the force signal. Results showed that the force profiles were usually less noisy than torque profiles, and so they decided to use force data exclusively for real-time detection. They define threshold values for the first derivative of the force of penetration, which in long bones are adjusted during the drilling of the first cortical wall in order to detect the transition of tissue and the breakthrough on the second cortical wall.

Ong and Bouazza-Marouf's method [10], presented in 1998, implemented a modified Kalman filter to convert the profiles of differences in drilling force between successive samples and/or the drill bit rotational speed into easily recognizable and more consistent profiles. After discarding the rotational speed as a parameter for detecting the breakthrough due to its inconsistency at low speeds, they concluded that breakthrough occurs when the K-FDSS (Kalman processed Force Difference between Successive Samples) drops to zero.

In 2001, Hsu et al. [11] presented a modular mechatronic system for automatic bone drilling in surgery. One of its major features is that it is easy to "add-on" devices that are compatible with commercially available motor-driven drills. The electric current consumed by the drill's DC motor is used as a sensing signal, and it was found that it has a direct relation with the cutting torque. A control box converts it into a voltage signal, and breakthrough is detected when the plot voltage vs. time presents a second peak and a sharp drop.

Lee et al. [12,13] developed in 2003 an algorithm for force control and breakthrough detection, which was successfully implemented in a three-axis robotic bone drilling system [14]. It consists of an inner loop fuzzy controller for robot position control and an outer loop PD controller for feed unit force control. Actual thrust force is measured with a load cell. This signal is combined with a force equivalent to the drilling motor's torque output and fed back into the outer loop. They based their breakthrough detection algorithm as a function of thrust force threshold information and trends in drill torque and feed rate.

In 2008 Coulson et al. [15] presented an application of an autonomous surgical robot system that was able to carry out the critical process of penetrating the bone tissue of the wall of the cochlea without penetrating the endosteal membrane located immediately inside the cochlea. A computer analyzes the force and torque imparted onto the drill in real time. Force is measured with a cantilever sensor on the drill bit and the torque is measured with the electrical power needed to turn the drill bit at a specified speed. Their control strategy stopped the burr when a force drop of 10 units was coupled with a torque rise of 10 units.

Other techniques considered the ultrasonically-assisted drilling of cortical bone. Alam et al. in 2010 [16] undertook an experimental investigation of forces and torque in conventional and ultrasonically-assisted drilling of cortical bone. Experiments were carried out with a bovine femur, from which cortical bones were cut. The results revealed that the penetration force and the torque dropped significantly when ultrasonic vibration was superimposed along the drill's longitudinal axis. In addition to the fact that the force was halved for the range of the drilling speeds selected, it was observed that chip removal from the drilling site was improved.

In 2014, Sun et al. [17] presented a technique that includes a state recognition of bone drilling with audio signals. They analyzed the sound generated during operation via the Fast Fourier Transform, which presents different characteristics due to the different kind of bone along the path of the drilling process. The Exponential Mean Amplitude and the Hurst Exponent were used to validate the energy characteristics and stability of the audio signals. Based on this and a time counter, they developed an algorithm to recognize the drilling state, which runs in an Embedded Drilling State Monitor that realizes real-time performance.

In recent works, Hu et al. [18,19] proposed a novel algorithm for state recognition based on the real-time force sensing of the drilling process. The algorithm takes into account the average value and the difference of the thrust force. It was implemented in a Robotic Spinal Surgical System (RSSS) to perform high-precision spinal surgeries using spherical and twist drills. To recognize the state transitions, threshold values were determined based on experiments with cattle's vertebrae that are considered to have similar mechanical properties to human vertebrae.

2.2. Methodologies based on wavelet signal analysis

In 1998 Allotta and Colla [20] applied a wavelet-based controller to a mechatronic drill for orthopedic surgery. The penetration velocity of the drill is generated on the basis of the wavelet analysis of the thrust force signal and the controller is capable to fulfill three different tasks corresponding to different specifications of the hole to be done in a long bone, which are to stop the drill: 1st as soon as the first cortical wall is cut, 2nd just before the second cortical wall and finally, as soon as the second cortical wall is cut.