TEMPERATURE REDUCTION BY CONTROLLED TRUS FORCE DURING AUTOMATIC BONE DRILLING IN THE ORTHOPEDIC SURGERY

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ABSTRACT.  
Background Many orthopaedic operations involve drilling before the insertion of screws into the bone. Usually drilling is executed manually, which brings problems. Bone overheating is the most important one. To avoid such problems and reduce the subjective factor, automatic drilling is recommended.
Methods As lots of parameters influence to the drilling process, the methods are experimental. They concern the experimental identification of the drilling technical parameters including the bone resistant force and the drilling process temperature. The resistant force and temperature are measured and plotted.

Results Specific drilling effects are revealed during the experiments. The temperature deviations are kept in the safe borders. The temperature reduction is achieved by controlled trust force during automatic bone drilling regime in comparison with hand-drilling one. Algorithms are created and their software realization is made. Curves of resistant force and temperature with respect of the time are presented. A proposed idea of ultrasonic vibration using for ultrasonically-assisted drilling of a cortical bone and applying a controlled trust force during automatic bone drilling regime is discussed.

Conclusions Automatic bone drilling can solve the high-temperature problems which arise during manual drilling. An experimental setup is designed to identify some parameters of bone drilling such as the resistant force due to variable bone density, the appropriate mechanical torque of drilling, the linear speed of the drill, and the electromechanical characteristics of motors, drives and corresponding controllers. The automatic drilling guarantees higher safety for the patient.

KEY WORDS: Automatic bone drilling; temperature minimization; experiments; orthopedic surgery

1. Introduction

Many researches have been recently devoted to robot application in orthopaedic surgery. To overcome the inaccuracy of hand-controlled positioning of orthopaedic surgical tools, a number of robotized systems have been developed during the last decade. In orthopaedic surgery it often requires the use of electrical instruments – cutting and drilling machines, saws and so on, which the surgeon holds in his hands during manipulation. By the literature reports drilling devices are used in approximately 95% of post-trauma interventions. This illustrates the persistent interest of researchers in such manipulations. Since orthopaedic screws are often implanted in bones, one needs to perform bone drilling beforehand. Yet, manual drilling tends to produce such problems as apertures larger than needed, tendon or blood vessel break, overheating, etc., which affect the accuracy and safety of the operation. Bone overheating is the most important one between them. Bone is a poor conductor of heat, with the thermal conductivity of fresh cortical bone in the region of 0.38±2.3 J/msK [1,2]. The stainless steel the drill bits usually made of, for comparison, is a much better conductor of heat than bone, having a conductivity of 14 J/msK.

However, some of the heat generated during drilling may be partially dissipated by the presence of blood and tissue but the temperature rise at the cutting edge in a deep cortical hole could be significantly high [3]. If bone is exposed for longer than 30 s at 50°C cellular necrosis will be induced [2]. When epithelial cells are exposed to a temperature of 70°C they will be damaged immediately, that when they are exposed to a temperature of 55°C for 30 s the result will be the same and at 45°C harmful effects will occur after 5 h [4,5].
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In general, the literature shows that if the temperature rises above 55°C for a period of longer than one-half a minute, serious damage will be done to the bone, which may take several weeks to fully recover.

In [6,7] it is shown that cutting speed had very little effect on temperature change above 55°C but that the force applied to the drill caused a much greater temperature increase. An idea to reduce the force applied to the drill is the usage of ultrasonic vibration for ultrasonically-assisted drilling of a cortical bone, proposed in [10]. Even the design of a micro vibration robot for orthopaedic surgery was proposed in [11], which has a sensor for torque-current connected to the end-effector and a control feedback loop.

Insofar as can be established from the literature, attempts at temperature measurement when drilling cortical bone have been carried out by placing thermocouples into the bone at given distances from the drilling area. Indifferent and sometimes contradictory results have been achieved using these methods. Because of the poor thermal conductivity of bone, its structural inconstancy and the great difficulty in modelling for heat-transfer purposes, embedding thermocouples in the bone adjacent to the drilling operation is not a satisfactory method of measuring the temperature effects [3]. An excessive temperature increase in the vicinity of the drill hole results in bone thermal necrosis which causes irreversible changes in the structure and physical properties of the bone [8]. In this case, the screw loosens reducing screw fixation stability and strength, and the necrotic tissue hampers healing and is infection-conductive [9]. All this affects patients’ safety, which is of crucial importance.

Based on the literature sources, it can be concluded that if temperatures greater than 45°C are reached then the temperature at the drill-bit cutting edge must be considerably higher with consequent severe damage to the bone surface of the hole. In the same time the temperature increased as the depth of the hole increased. Speeds of 800-1400 rpm should be used and such a drilling mode provides the best cutting conditions and maintaining temperatures at a manageable level. Such a drilling mode can be realized by the application of robots in the orthopaedic surgery, which also assures high precision and accuracy of manipulations and that all reflects to the better patient’s safety.

The aim of the paper is to present experimental evidence of the advantages of automatic bone drilling concerning the temperature reduction by controlled trust force, confirming these advantages, discuss and analyse the temperature effects occurring during bone drilling.

2. Experimental setup

We modified and improved the developed the experimental set up presented in [12, 13]. Our experimental approach was chosen in view of the complex character of the object under study. As it was mentioned above, modelling was very difficult to
accomplish since many parameters including unknown ones had to be taken into account. Yet after performing many experiments it was concluded that a robot for automatic bone drilling should incorporate components capable of guaranteeing:

- Torque up to 1.5 Nm
- Force along the translation up to 100 N
- Force sensor range up to 100 N
- Temperature not over 52°C
- Accuracy less or equal to 0.5 mm for the drilling depth or length of the bone hole.

At the same time, robot dimensions and mass should be as small as possible.

Note that some parameters of a bone drilling operation can be experimentally identified, for example, the values of some parameters, based on the experimental evidence. Yet those very values which were obtained experimentally varied when the drill bit was replaced by a sharpened one.

2.1. Components mounted in the experimental setup

**Linear actuator 43000–17.** It is a stepper motor with an embedded screw for linear motion, highly accurate at low speed, small in size, translation of 1 mm for 4032 micro steps (1.80°/step, 0.0158 mm/step).

**Brushless DC motor MAXON.**

Such motors have many advantages: better speed-versus-torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, tough structure. Note also the large torque despite the small motor size. The space and weight are factors guaranteeing torques of up to 1.7 Nm.

The controllers comprise two main components: a controlling device and a power drive with built-in PID-regulators for positioning and speed. They are: **Controller / Driver** TMCM-1110 to control a linear actuator supplied with the one-axis stepper motor 43000-17; **Servo Controller / Driver** for BLDC MAXON.

The sensor system comprises: **Force sensor** LMB-A-200N (Kyowa) for the bone resistant force; **Temperature sensor** SP i-tec 2005D, an infrared non-contact temperature measuring instrument.

A test performance is presented below (Fig.1), where a beef bone is fixed.

![Fig. 1. Drilling execution.](image-url)
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3. Control algorithms

Control algorithms are executed in the specific program environment TMCL-IDE. The commands can be executed immediately after their input or the program can be downloaded in the controller to perform autonomous execution of commands. In each cycle, the program recognizes the current state, executes the corresponding algorithm and decides the transition to the next state according to preliminarily specified criteria.

The algorithm which is followed for the current calculation of the “next target position” of the stepper motor depends on the force sensor data. The actual force sensor data are compared to previously given values to check whether the safety requirements to prevent exceeding the limit value are being kept.

An algorithm to identify the value of the resistant force initiated during drilling is executed [13]. This value is related to the manipulation characteristics of the object and with the diameter of the drill bit. The value found is used to decide whether to end bone cortex drilling.

4. Experimental results

Certain effects are discussed which occur under an automatic bone-drilling regime and can be registered only during the course of an experiment. On fig.2 and fig.3 the temperature during manual and automatic drilling throughout the entire bone are presented. The vertical axis shows the temperature and the horizontal axis shows the time. Under the same experimental conditions the maximal value reaches 50°C and 42°C during drilling time 15 s and 25 s, correspondingly.

![Fig. 2. Temperature during manual drilling throughout the entire bone (drill bit Ø6 mm).](image1)

![Fig. 3. Temperature during automatic drilling throughout the bone (drill bit Ø6mm).](image2)

There is a great variation in the hardness of the different bones in a particular body and there can be a great variation in the hardness of a particular bone due to the age, sex, race or medical status of the person. This variation will cause a consequent variation in the thrust, torque and power values of a particular drilling operation. Because of that, at the beginning, the resistant force is identified for a specific object.
(patient), taking into account the patient’s characteristics [14]. The resistant force is presented on fig.4. The experimental data are smoothed. The best results are obtained when approximation polynomials of the 19th and 21st degree are used, respectively. We use these polynomials to evaluate the force limits not to be exceeded during drilling. Figure 4 shows that the span between the numerical values and the measurement data is relatively large, which may disturb the algorithm and program execution. The approximations help to find the type and size of appropriate filtration, recognize the local maximums and their number, i.e. recognize both cortices. The estimation of resistance force limits prevents a specific bone from possible crushing. The same approach is applied to hole depth and bone cortex size.

![Fig. 4. Approximation of the resistant force by 19th degree polynomial function.](image)

5. Discussions and conclusions

The proposed experimental setup was designed to identify certain characteristics of the bone drilling process such as resistant force owing to variable bone density, appropriate mechanical torque during the manipulation, linear speed and the electromechanical parameters of motors and drives. The experiments also disclosed a solution to the overheating problem. A plug-in temperature sensor was mounted in the experimental setup to guarantee temperature recording before, during and after drilling. Our results showed that a small variation in the drilling parameters yields a temperature increase. The total drilling time never exceeds 20 s, really 6-10 s and the maximal temperature is less than 50°C. That is in agreement with the result mentioned above that the bone must not be exposed for longer than 30 s at 50°C. The comparison between hand and automatic drilling shows the controlled trust force almost twice decreases the resistant force reflecting to the temperature reduction, which can be realized in automatic drilling mode only. The precise drilling performance proves the advantage of using drilling robots in surgery, assuring in the same time more reliability and safety.

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