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ARTICLE

Design and Implementation of a Control System to Mitigate Osteonecrosis in Orthopedic Bone Drilling Procedures

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ABSTRACT

The drilling process in orthopedic surgery can sometimes lead to an undesired increase in temperature, which can cause serious damage to bones and soft tissues. This overheating is typically identified as a temperature above 47 °C, known as the critical limit, and can result in the condition known as osteonecrosis. This study aims to develop a new control system, using a proportional-integral-derivative (PID) controller, to prevent overheating and the resulting osteonecrosis. The bone temperature is constantly measured using a thermocouple and, when it reaches the critical temperature of 47 °C, the cooling device is activated by the PID-controlled system. This new control system makes the drill machine with cooling device more user-friendly and allows surgeons to set a desired temperature level manually.

Keywords: Bone drilling; Orthopedic surgery; Osteonecrosis; PID controller; Driller mechanism

1. Introduction

Biocompatible medical components are commonly used in orthopedic surgery to heal broken bones. To fix fractures, surgeons use a surgical drill to secure plates with screws, as shown in **Figure 1**. In bone drilling procedures, there is often overheating between the drill and the base material due to high friction, which can cause failures. When the undesired temperature increase exceeds a critical value, it can seriously

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damage the bone and soft tissue in the bone drilling process. This can lead to osteonecrosis, a condition where bones and soft tissue remain anemic due to the failure caused by overheating [1]. There are several studies available in the current literature about the critical value of temperature. Hillery and Shuaib [2] studied and found that bones are seriously damaged when the temperature rises above 55 °C in 30 seconds. Eriksson et al. [3] studied in vivo and presented that the cortical bone of a rabbit exhibited thermal necrosis above 47 °C in 60 seconds. Augustin et al. [4] also reported that the temperature can increase above 47 °C, which can cause irreversible osteonecrosis during the bone drilling process.

Biocompatible medical components are commonly used in orthopedic surgery to heal broken bones. To fix fractures, surgeons use a surgical drill to secure plates with screws, as shown in **Figure 1**. In bone drilling procedures, there is often overheating between the drill and the base material due to high friction, which can cause failures. When the undesired temperature increase exceeds a critical value, it can seriously damage the bone and soft tissue in the bone drilling process. This can lead to osteonecrosis, a condition where bones and soft tissue remain anemic due to the failure caused by overheating. There are several studies in the current literature that examine the critical value of temperature during bone drilling procedures. Hillery and Shuaib [2] found that bones can be seriously damaged when the temperature exceeds 55 °C in 30 seconds. Eriksson et al. [3] studied the effects in vivo and discovered that the cortical bone of a rabbit suffered thermal necrosis when the temperature exceeded 47 °C in 60 seconds. Augustin et al. [4] also reported that temperatures above 47 °C during bone drilling can cause irreversible osteonecrosis.

There are many papers available on bone drilling processes. Papers related to bone structures [3,6-8] and the effects of processing parameters, such as spindle speed and feed rate, drill geometry, have been studied [9-11,4,6]. The processing parameters are extremely important and should be selected at an optimal level because the selection of improper parameters can cause tissue damage [12-15]. The most important of these parameters is the temperature in terms of bone and soft tissues. Many different types of studies are available in the literature to control bone temperature rise. Augustin et al. [16] designed a two-step cooled-drill internally and investigated the increasing bone temperature value.

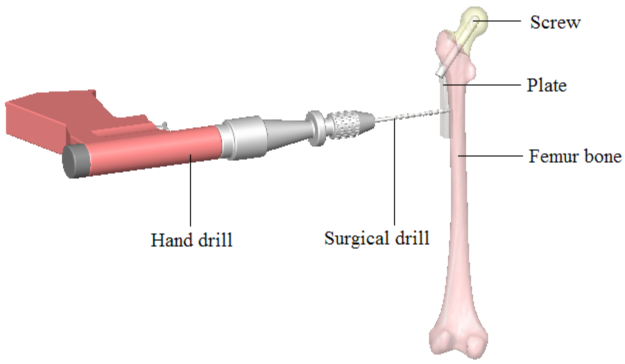

Figure 1. Surgical bone drilling process [5].

The aim of this study is to develop a new control system to control and prevent the undesired temperature rise during the bone drilling process. The new system is developed to control the bone driller mechanism developed in the previous study [5,1]. The bone driller mechanism that was explored previously is having a coolant device that works in a closed-loop to cool the drill bit and bone. The developed new control system is working with Proportional-Integral-Derivative (PID) controller system. The PID system, a kind of sensor or control loop mechanism, is widely used in industrial applications to control the mechanism. The developed PID controller system controls and activates the coolant device of the driller mechanism when the bone temperature rises undesirably. The PID control system is a user-friendly mechanism and surgeons are also able to set up the critical temperature level or desired temperature limit manually. The bone temperature level has been controlled to prevent bone damage caused by overheating.

2. Materials and methods

2.1 Development of PID controller system

The drilling mechanism is composed of three main components, the drill bit, drill chuck, and closed-loop cooling device, as shown schematically in **Figure 2**. As seen, the drill and drill chuck work together as a combined drilling tool that has cooling devices designed internally in both the drill and drill chuck through hidden cooling slots. The drill bit is mounted on the drill chuck, which is compatible with different diameters of drill bits [5,1].

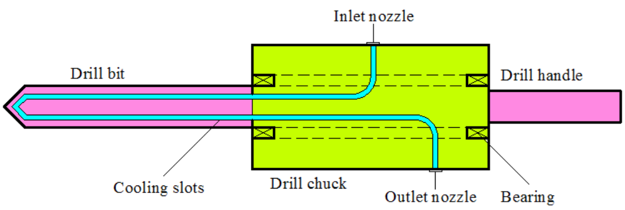

Figure 2. The schematic view of the surgical driller system [5].

The PID control system is developed and inserted into the experimental set to control the coolant device in the case of the bone temperature level rise during the drilling. The developed controller system is mounted to a mini-CNC milling machine for the drilling experiments as seen in **Figure 3**. In the experiments, a thermocouple for temperature measurement and a cooling motor, were switched with a PID controller system to keep the desired bone temperature level. To measure the bone temperature values during the drilling, a thermocouple device has been. These values are saved in the PID controller device as in analog data. During the drilling process, when the bone temperature level reaches the critical temperature value of 47 °C, the cooling system is activated by the controller system. In literature, the critical values of the bone temperatures are variable based on the bone structures but, it is commonly selected as 47 °C, mentioned above. The tissues surrounding the drilled bone are affected when the bone temperature exceeds the critical value so that the desired temperature level can be selected lower by surgeons using the controller system.

The measured temperature value is defined as the peak value (PV) and the desired temperature value is called the set point (SP). When these two values (SP and PV) are compared to each other, the difference between them is called a temperature-error, calculated with Equation (1). Compensating the error is provided by the PID controller equation as given in Equation (2). In order to compensate for the temperature differences, a required Pulse Width Modulation (PWM) is generated by the PID controller system and then the cooling motor is activated instantly. The coolant will be transferred into the chuck and it will circulate through the cooling channels of the surgery drill. The PID controller device will continuously generate the PWM by calculating the error rate. The working system of the PID control system is shown in **Figure 3**. The flowchart of the PID control system is shown in **Figure 4**.

$$e = SP - PV \tag{1}$$

$$U_{PID} = K_p e + K_i \int edt + Kd\left(\frac{de}{dt}\right) \tag{2}$$

where, K_p: Proportion gain, K_i: Integral time constant, K_d: Derivative controller.

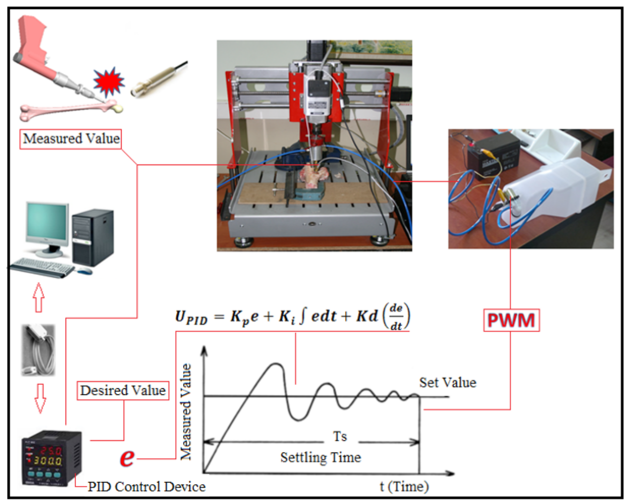

Figure 3. The working system of the PID controller.

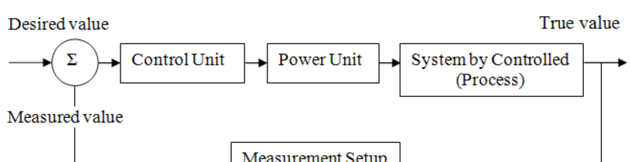

Figure 4. The flowchart of the PID controller system.

3. Results and discussions

The drill bit and cooling system were mounted and fixed on a desktop-type mini CNC milling machine as seen in **Figure 4**. The thermocouple and cooling motor were clamped and connected to the PID device. The bone drilling processes were performed using the desktop-type mini CNC milling machine. In order to perform the drilling process, a fresh calf femur, a 3-year-old, was used in the mini CNC machine after completing the necessary all samples, tools and equipment. The fresh bone was obtained from a butcher. The bone drilling experiments were performed at a spindle speed (n) of 800 rpm and a feed rate (Vf) of 25 mm/min. When the bone temperature reaches 47 ºC, the PID control system will be activating the cooling motor and system as seen in **Figure 5**. The coolant water is circulated inside the drill bit to cool.

In the drilling experiment of the fresh bovine bone (femur) samples, the drill bit is cutting (drilling) the cortical-cancellous-cortical bones, respectively. The drilling experiments were performed at room temperature conditions using/without the PID controller. During both drilling experiments, the bone temperatures were measured instantly and the results were saved in the computer as in two different curves based on the critical temperature value of 47 ºC. The bone-measured temperatures were plotted as a function of time (sec) shown in **Figure 5**. As seen, the curves are labelled as "No control" and "PID control". Both cortical and cancellous bone temperatures were generally measured lower than 47 ºC when using the PID controller since the cooling system is activated, if necessary, during the drilling process. These measured bone temperatures were shown with the curve named "PID control". As can be seen from the figure, the cancellous and cortical bone temperature was measured after 8.1 seconds slightly higher than the 47 ºC but it is not disturbing.

The spindle speed (n) and feed rate (Vf) are the most important drilling processing parameters to affect bone necrosis. The bone temperature levels that occurred during the drilling can be controlled by the "n" and "Vf". Several papers presented that "rpm" is increasing, and bone temperature is increasing due to overheating on the surgical drill bit or cutting tool [17-19]. The overheating results the bone tissue necrosis. However, the most amount of heat is absorbed by the bone chips that are removed away from the drilling zone. Increasing the "rpm" of the process is accelerating the chip removal from the drilling zone which reduces the bone temperature levels [6,20-25]. Therefore, it is realized that the bone temperature levels during the drilling are depending on the drilling process conditions. The temperatures that occurred in the bone during the drilling can easily be controlled using the developed PID control system.

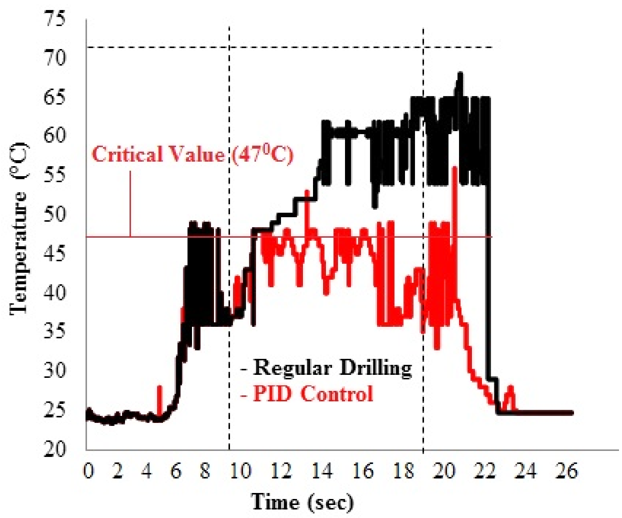

Figure 5. Bone temperatures during bone drilling.

4. Conclusions

In this study, a PID control device/system is developed to control the new driller system developed previous study [5]. The PID control system is controlling and activates the cooling system device and motor of the new driller system when the bone temperatures reach 47 °C during the bone drilling process. In addition, the developed PID controller system is user-friendly since surgeons are also able to set up a critical or desired temperature level manually during the drilling operations. Based on the results obtained in this study, the developed PID controller device is providing a valuable result without osteonecrosis during the bone drilling process at low "rpm".

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Conflict of Interest

There is no conflict of interest.

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