Robot-Assisted Surgical Platform for Controlled Bone Drilling: Experiments on Temperature Monitoring for Assessment of Thermal Bone Necrosis

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Abstract—**One of the most serious problems encountered during bone-drilling is the generation of heat, as the increase in temperature of the drilling site may result in thermal injury due to bone necrosis phenomena. So developing a method for predicting, controlling and preventing bone ischemic states during surgical interventions would be a great improvement, regarding adequate prostheses fixation and patient recovery. Implementing a predictive equivalent thermal circuit for necrosis assessment involves performing a number of experimental measurements for model parameter identification.**

Thereby, several drilling experiments on bovine bone have been conducted, using a Robot-Assisted Surgical platform developed at CEIT, where the temperature evolution of the drilled area has been monitored immediately post-drilling, using Infrared thermography. The maximum temperature values reached for different sets of machining parameters have been established and natural convective cooling patterns have been characterized by obtaining an average value of the thermal time constant of the system.

Keywords—**Robot Surgery, Drilling Parameters, Necrosis.**

I. INTRODUCTION

Among the different machining processes that are regularly applied during surgical interventions, drilling is probably the most frequent process since in various clinical specialties it serves as a preliminary step in the insertion of pins and screws during the reduction, repair or fixation of bone fractures and installation of prosthetic devices [1].

However, several key problems are often reported in the literature [2, 3, 4]: difficulties in maintaining freehand control of the drill, even using a drill guide; attaining geometric accuracy in hole size, location and orientation in order to ensure a suitably rigid mechanical fixation or the *slippage* problem, where the drill bit tends to "walk" or slip on the bone surface as it begins to cut the work piece.

Some of the above issues can be addressed by introducing technological developments that include robotic systems for assistance during surgical procedures; these are known as Robot-Assisted Surgical (RAS) platforms [5, 6]. They have the potential to improve the safety and effectiveness of conventional surgical procedures by ensuring levels of precision, dexterity and safety that are unattainable by other means. Customized drilling tools are designed for these platforms in order to perform complex drilling operations safely, yielding real-time control architectures.

However the heat generation during bone machining, produced by the plastic shear deformation of the bone chips and the friction between the drilling tool and the bone, is still an open issue [1, 3]. In general, many surgical procedures depend on the degree of stability of the screws that fix the implanted device to the bone; consequently, the loss of bone at the drilling site may lead to implant failure. Heat generation during drilling causes a substantial increase in the temperature of the drilled area, and this may result in thermal injury due to ischemic bone necrosis phenomena, which cause an undesirable increase in bone resorption around the implanted screws. The threshold for considering thermal necrosis has been defined as temperature values beyond 47 ºC lasting for 1 minute [2, 7].

There are different ways in which to maintain osteonecrosis levels to a minimum. It is extremely important to define sets of machining parameters that are suitable for surgical procedures and to relate the effect of the machining parameters to the temperature increase at the drilling site, the most common effective parameters being cutting speed (N_s), feed-rate (f_r), applied drill force, tool type and tool tip geometry [7]. Also, the beneficial effect of external saline irrigation, regarding the immediate reduction of temperature at the drilling site, is well documented in literature [8].

Introducing a real-time predictive control model for assessment of bone necrosis, such as an equivalent thermal impedance circuit, could be a valuable tool during surgical interventions to avoid possible prostheses fixation problems. In order to build the mathematical model of the predictive thermal circuit, a system parameter estimation process must be performed from experimental data measurements.

Therefore, the main goal of this work is to perform several *in vitro* drilling experiments on bovine bone, using a Robot-Assisted Surgical (RAS) platform together with a customized drilling tool, both developed at CEIT, where bone temperature is monitored immediately post-drilling by means of Infrared (IR) thermography equipment. Maximum temperatures attained during drilling, expected at the bottom of the drilled hole [9], are calculated from acquired data. In addition, natural convective cooling patterns of the system are obtained from the temperature evolution and the time

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code of the IR recording; characterizing the thermal system relaxation through its time constant is essential as this provides the needed information for later system parameter identification.

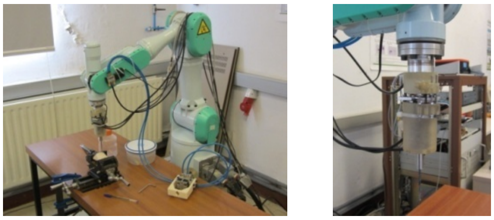
The remaining sections are arranged as following: section II details the methodology and experimental procedure; results from the experiments are given in section III and discussed in section IV. Finally, section V presents the conclusions of the study and future work.

II. MATERIALS AND METHODS

A. Description of the Surgical Platform

The RAS platform developed at CEIT was conceived to provide assistance during transpedicular fixation surgical procedures [6]. The robot used in this platform is a PA10-7C (Mitsubishi Heavy Industries, Japan), an industrial robotic arm with 7 degrees of freedom that offers a high level of dexterity thanks to its redundant joint (Figure 1a).

The software platform chosen for executing the robot control loop is the Real Time Application Interface (RTAI) for the Linux OS. RTAI is an extension of the Linux kernel that enables real-time capabilities in the OS, allowing a dual-kernel structure: the standard Linux kernel and real-time kernel. The data acquisition board used is the Sensoray-626.



(a) RAS platform **(b) Surgical Tool**

Fig. 1 RAS platform and drilling tool prototype developed at CEIT

A customized drilling tool (Figure 1b) was designed for performing the drilling procedure. The implemented hardware architecture is presented in Figure 2.

A conventional, stainless steel twist drill-bit that is 3.2 [mm] in diameter and 70 [mm] long and has a point angle of 90º, was used in the drilling experiments.

B. Bone Sample Harvesting and Preparation

Bone specimens from adult bovine cattle were collected from a local slaughterhouse and preserved in a refrigeration chamber. Samples were obtained from a diaphyseal distal radius, which was chosen as a suitable long bone for drilling. The thickness of the cortical bone of the test work pieces ranged from 7 to 9 mm.

Prior to conducting the bone drilling experiments, a surgical scalpel was used to clean the bone samples of tissue remnants and marrow; later the samples were submerged in a sodium hypochlorite bath (30 min), a hydrogen peroxide bath (2 hour) and preserved in saline buffer at room temperature.

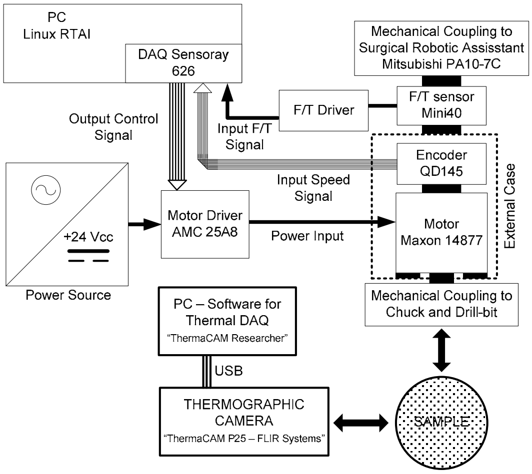


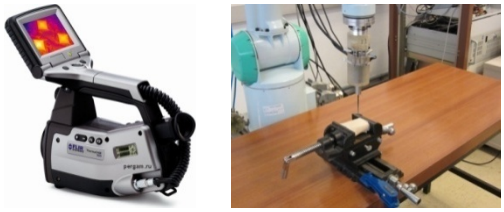
Fig. 2 Hardware architecture of the drilling tool and experimental setup

C. Measuring Equipment

As has been previously stated, temperature distribution measurements were performed using IR thermographic equipment. IR cameras detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation, called *thermograms* or *temperature maps*.

Measurements were taken with the ThermaCAM P25 (FLIR systems, Sweden) thermographic camera, with a focal plane array of non-refrigerated micro-bolometers of 320x240 sensors (see Figure 3a). The camera was placed orthogonal to the bone drilling surface, at a distance of 33 [cm].

The emissivity calibration of the bone (ε_{bone}) was performed by using a piece of black tape stuck to the bone surface (knowing *a priori* that $\varepsilon_{tape} = 0.93$) and a *datalog* with two thermocouples in order to measure the bone-tape surface temperature and the environment temperature. It was determined that $\varepsilon_{bone} = 0.41$.



(a) ThermaCAM P25 **(b) Experimental Setup**

Fig. 3 IR camera and experimental setup

D. Testing Procedure

The set of parameters used in this work to carry out the bone drilling experiments (see Table 1) were determined by taking into account the experience of other research groups whose experiments have been described in the literature [2, 7].

Sample A was tested after being removed from the saline buffer solution for three hours, and sample B was tested after immediate removal from the saline buffer solution.

Bone work pieces were held using a clamp, which allowed for adequate placement of the bone probe with respect to the robotic arm (see Figure 3b) for orthogonal drilling.

For each experiment, the temperature measurement was performed immediately after the withdrawal of the drilling tool. This methodology will be discussed in section IV.

Table 1 Experimental parameters for bone drilling

Test	Sample	Feed Rate [mm/s]	Cutting Speed [rpm]
1	A	0.5	3000
2	A	0.2	1500
3	A	0.2	3000
4	A	0.5	1500
5	B	0.2	3000
6	B	0.2	1500
7	B	0.5	3000
8	B	0.5	1500

III. EXPERIMENTAL RESULTS

Temperature distribution maps of the drilled bone samples were obtained using ThermaCAM Researcher® software (FLIR systems). Figure 4 shows various thermograms from some of the tests.

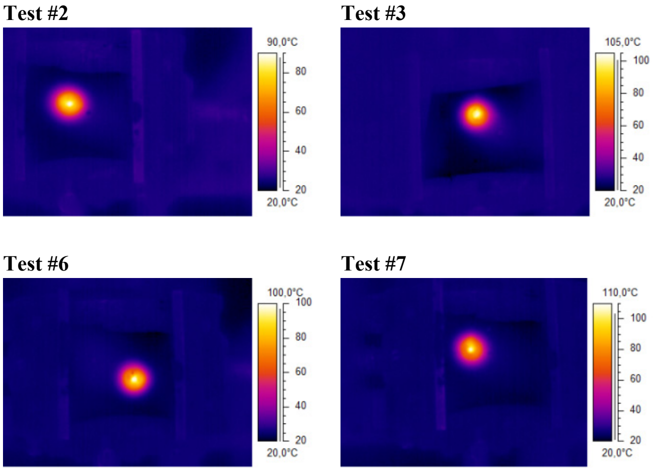

Test #2
Test #3
Test #6
Test #7

Fig. 4 Temperature maps obtained from Tests 2, 3, 6 and 7

Using the available image processing tools in this software, the immediate post-drilling 'maximum temperature value' was calculated by averaging the values of a 1 mm diameter circular Region of Interest (ROI) which contained the peak temperature found in each image. Results for all the experiments are presented in Figures 5 and 6, where the influence of the drilling parameters and the *in vitro* conditions of the samples is shown.

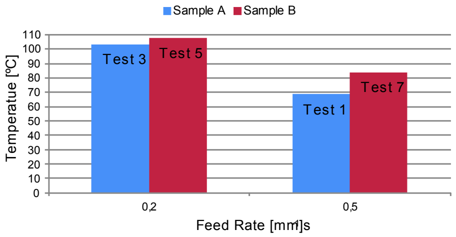


Fig. 5 Average maximum temperature in drilling area, $N_s = 3000$ [rpm]

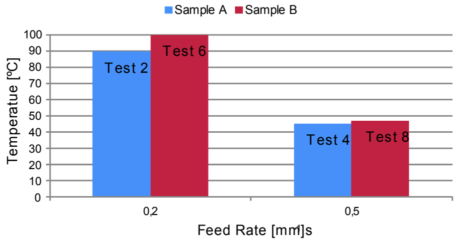


Fig. 6 Average maximum temperature in drilling area, $N_s = 1500$ [rpm]

The characteristic natural convection curves were obtained from each experimental test data, being known the time code of the acquired images, by means of regression analysis. The purpose of carrying out this analysis was to obtain the relaxation time constant of the thermal system in order to characterize the *in vitro* cooling process.

$$T(t) = T_{env} + \left(T_0 - T_{ref}\right) \cdot e^{\frac{-t}{\tau_b}} \qquad (1)$$

Experimental cooling curves follow the exponential fitting pattern presented on Equation 1, where $T(t)$ is the temperature evolution, T_{env} is the environment temperature, T_{ref} is the bone reference temperature, T_0 is the initial temperature of the heated system and τ_b corresponds to the relaxation time constant, measured in seconds. According to thermocouple measurements, the environmental temperature during the experiments was $T_{\text{env}}=21.5$ [ºC]; also, the bone reference temperature has been considered the same as T_{env}.

Once all time constants were obtained for the different experiments, a statistical analysis was performed to obtain the mean and standard deviation values for τ_b. It was determined that $\tau_b=45.02 \pm 15.81$ [s], yielding an average correlation coefficient of $R^2=0.994$.

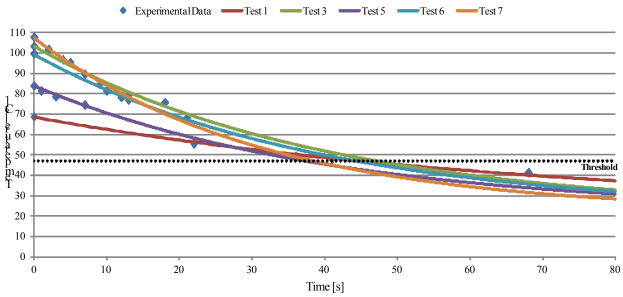


Fig. 7 Exponential fitting for Tests 1, 3, 5, 6 and 7

IV. DISCUSSION

The influence of the feed rate is clearly a determining factor in temperature increase: for a higher feed rate, there was a large reduction in temperature increase (average reduction of 40%), though caution is recommended in case it is not possible for the tool to remove bone material at such a rate. The difference in the spindle cutting speed between experiments also proved that temperature rise is lower for lower cutting speeds (average reduction of 25%). It was noted that for wet sample (B), the temperature rise was slightly higher than for dry sample (A).

Slippage problems were observed during the experiments, though they were minimized because of the use of the RAS platform; also, increasing the feed rate helped minimize the slippage effect. Geometric accuracy and tool guidance were greatly improved over the preliminary manual tests that were performed prior to this experimental work and thus were not considered of interest.

The use of thermocouples was discarded because it is an invasive method which requires an extremely accurate definition *a priori* of the thermocouple and the drilled hole relative locations, thus limiting the number and type of experiments to be performed on a sample. Additionally, data obtained from a thermocouple would consist of indirect measurements of the considered ROI, at the base of the hole.

However, since thermal radiation is a process by which electromagnetic radiation is emitted by a heated surface, the IR camera is able to monitor only surface temperatures; so it is not possible either to directly measure the temperature of the bottom of the hole during the drilling process. Nevertheless, assuming that bone is a system with high thermal inertia, it was postulated *a priori* that natural convective cooling over time should be slow, as shown in Figure 7. Based on this, we decided that it was suitable to perform the drilling operation and then place the IR camera immediately after finishing in order acquiring the images of the maximum initial temperature and the cooling process. In order to assess bone necrosis, it seemed reasonable that for such high temperatures such small inexactitudes (up to 6-8 [ºC] over an initial temperature of 100 [ºC]) were acceptable.

More experimental testing needs to be performed for increasing the statistical significance of τ_b. Different in vitro conditions should also be tested as in actual operating theaters conditions are more adverse (higher reference temperature, worse convection properties…), thus increasing the value of τ_b and introducing the need for irrigation, which was not considered here given the actual *in vitro* testing conditions.

V. CONCLUSSIONS AND FUTURE WORK

Several bone drilling experiments were successfully performed using our RAS platform. Thermograms were acquired using IR equipment and the influence of different drilling parameters has been shown. The time constant of the thermal system has been obtained through statistical analysis, yielding a highly significant correlation coefficient.

This work corresponds with the experimental stage of a broader project, where a predictive model for assessment of thermal bone necrosis will be derived, provided that more tests will be conducted in order to gain statistical significance.

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