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Drill wear monitoring in cortical bone drilling

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ABSTRACT

Medical drills are subject to intensive wear due to mechanical factors which occur during the bone drilling process, and potential thermal and chemical factors related to the sterilisation process. Intensive wear increases friction between the drill and the surrounding bone tissue, resulting in higher drilling temperatures and cutting forces. Therefore, the goal of this experimental research was to develop a drill wear classification model based on multi-sensor approach and artificial neural network algorithm. A required set of tool wear features were extracted from the following three types of signals: cutting forces, servomotor drive currents and acoustic emission. Their capacity to classify precisely one of three predefined drill wear levels has been established using a pattern recognition type of the Radial Basis Function Neural Network algorithm. Experiments were performed on a custom-made test bed system using fresh bovine bones and standard medical drills. Results have shown high classification success rate, together with the model robustness and insensitivity to variations of bone mechanical properties. Features extracted from acoustic emission and servomotor drive signals achieved the highest precision in drill wear level classification (92.8%), thus indicating their potential in the design of a new type of medical drilling machine with process monitoring capabilities.

1. Introduction

Along with the development of new surgical approaches and techniques, bone drilling has become mostly routine and continuously increasing medical intervention. Bone tissue is formed by organic and mineral phases whose interactions result in complex mechanical and thermal properties. All bone drilling interventions include heat generation due to the friction between tool, bone and chips, which can significantly influence the post-operative recovery. Hence, novel drilling techniques have been used to study the interaction between the drill and bone in order to reduce drilling forces and improve chip removal from the drilling site [1–3]. Although mechanisms of thermal bone damages are still not thoroughly explained, it is a known fact that temperature rise in the drilling zone can cause thermal osteonecrosis, which prevents quality tissue healing and bone regeneration [4,5].

There are several factors influencing drilling temperature variations and potential occurrence of thermal osteonecrosis: mechanical characteristics of the bone and its cortical thickness [6,7], drill design and geometry [8–11], inefficient external cooling effect due to low bone thermal conductivity [12], inadequate cutting speeds and feed rates [13–15], improper tool position/trajectory which increases friction between the drill body and the hole surface, and drill wear. Drill wear is among those factors with the highest impact on heat generation during bone drilling. It is an unavoidable and irreversible process which increases friction in the cutting zone. Besides negative thermal impact, it causes higher cutting forces and tool vibrations, which can result in the cutting edge breakage, or complete drill breakage in the flutes or shank zone. These situations cause mechanical bone damages, which also have negative impact on the post-operative therapy progress.

Several studies of drill wear effect on temperature variations conducted in the field of oral and maxillofacial surgery point to the strong and proportional relationship between tool wear dynamic and bone drilling temperature rise [16–19]. At the same time, some researchers emphasised the frequent usage of worn drills in medical interventions, as well as absence of hospital standards and activities focused on drill wear identification and tool labelling [20]. It is therefore logical to presume that precise and reliable drill wear models could become important elements in the reduction of the occurrence of bone tissue damages. Their role would be particularly important in the development of semi- or completely automated advanced medical drilling systems.

In the past 25 years, numerous studies on drill wear monitoring have been published, mainly focused on industrial applications [21]. Drilling process dynamic in industrial applications usually differs from that related to the bone drilling in terms of different types

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of drills, bone vs. industrial workpiece material characteristics, machining parameters, cooling methods, etc. Nevertheless, methodology used in designing industrial tool wear monitoring systems based on multi-sensor approach and nonlinear modelling could also be potentially applicable in medical drill wear identification. However, to our knowledge, there is still a lack of tool wear monitoring solutions specifically designed for medical applications, or experimental studies involving the implementation of some already designed and tested industrial monitoring systems in bone drilling applications. Although several models for temperature estimation in bone drilling have been proposed [22,23], none of them includes drill wear identification.

There are two major obstacles which prevent precise tool wear level quantification. Direct measurement of tool wear during the cutting process is not possible due to constant contact between bone and drill cutting edges. It can only be estimated using tool wear features extracted from different types of process signals and other known machining parameters (cutting speed, feed rate, drill characteristics). Additionally, industrial applications have shown that tool wear is usually highly nonlinear and sometimes even a partially stochastic process. Similar characteristics can be expected in bone drilling due to the complex interrelation of all aforementioned process parameters. The complexity of wear process in industrial applications motivated many researchers to experiment with different types of computational intelligence algorithms, primarily artificial neural networks, to build reliable and accurate wear models. Artificial neural networks gained such popularity because of their nonlinear modelling capabilities based on parallel processing and integration of system/process data (in this case, drill wear features and machining parameters).

Taking all this into consideration, the aim of this experimental study was to analyse the performances of the multi-sensor based medical drill wear classification model, and its potential for application in the next-generation medical drilling machines. Drill wear features were extracted from force, current and acoustic emission signals, and then processed using Radial Basis Function Neural Network (RBF NN), which is known for short learning procedure, as well as simple and quick hidden layer structure adaptation.

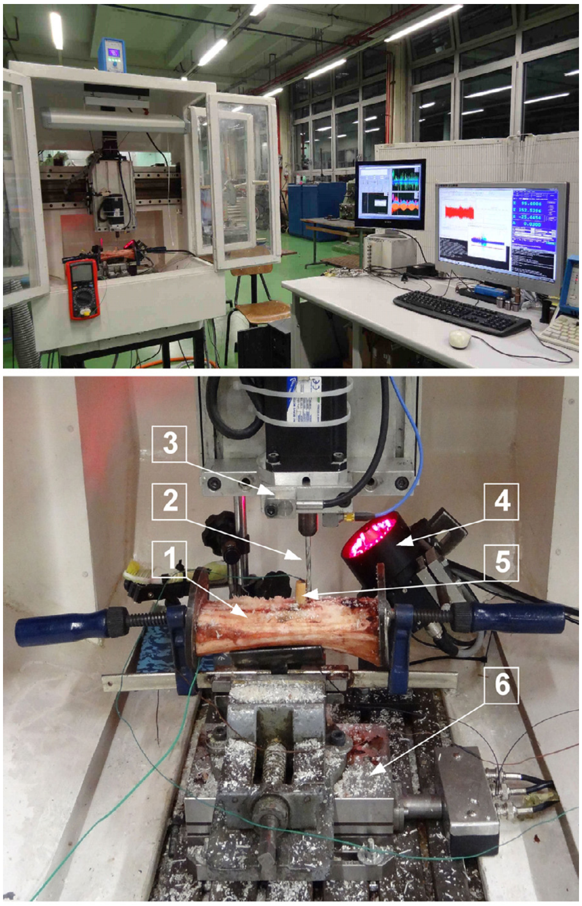
2. Methods

2.1. Experimental setup and parameters

Experimental work has been performed using the custom-made 3-axis bench-top mini milling machine adjusted for the purpose of the bone drilling research (Fig. 1).

The machine has been retrofitted with the 0.4 kW (1.27 N m) permanent magnet synchronous motors with integrated incremental encoders (type Mecapion SB04A), corresponding servomotor drives (DPCANIE-030A400 and DPCANIE-060A400), ball screw assemblies and LinuxCNC open architecture control (OAC) system. Apart from the control loop referent currents taken from the main spindle and feed drives, cutting forces have been measured using triaxial Kistler piezoelectric dynamometer 9257B coupled with 5017B charge amplifier, and acoustic emission (AE) signals using Kistler industrial sensor type 8152B1 coupled with 5125B interface module. Direct observations of drill cutting edges were done by industrial camera type DMK41AF02 equipped with the telecentric lenses type TC2309. The experiment was further characterised with the following features:

(1) Drill type and tool wear levels
Drilling has been performed using Komet Medical 4.5 mm standard medical drills (type S2727.098), which were not subjected to sterilisation conditions. Three tool wear levels (TWL) were analysed – sharp drill (SD), medium worn drill (MWD) and worn drill (WD). Measurements were first taken while drilling with completely sharp drill. After completing the experiment for the first TWL, the drill was used to bore an additional 100 holes, at 900 rev/min and 0.3 mm/s feed rate, until it was worn out to the second TWL. The same procedure was repeated for the second and the third TWL. After approximately 560 holes altogether, drill has worn out to its final condition related to the WD level. Flank wear was observed as a dominant type of drill wear. This can be seen in Fig. 2, where flank wear zones on one cutting edge are presented at the beginning and at the end of experiment for every analysed TWL. Practically identical flank wear areas have been noticed on both cutting edges.



1) Bone specimen
2) Medical drill
3) Acoustic emission sensor
4) Industrial CCD camera with telecentric lens system
5) Temperature probe with thermocouple
6) Force sensor

Fig. 1. Experimental setup.

(2) Cutting speeds and feed rates
Twelve combinations of feed rates (0.01, 0.03, 0.05, 0.1 mm/rev) and cutting speeds (10, 30, 50 m/min) have been analysed. These cutting speeds correspond respectively to 707.4 rev/min, 2122.1 rev/min and 3536.8 rev/min, while feed rates fall within the interval (0.12 mm/s–5.9 mm/s) as presented in Table 1. The combinations of machining parameters have been chosen with regard to existing clinical practice based on hand-held drilling machines, as well as potential development of completely robotised high-speed drilling systems. Measurements for each combination of machining parameters and every tool wear level were randomly repeated 10 times.