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The effects of cutting parameters on cutting forces and heat generation when drilling animal bone and biomechanical test materials

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ABSTRACT

The research presented in this paper investigated the effects of spindle speed and feed rate on the resultant cutting forces (thrust force and torque) and temperatures while drilling SawBones® biomechanical test materials and cadaveric cortical bone (bovine and porcine femur) specimens. It also investigated cortical bone anisotropy on the cutting forces, when drilling in axial and radial directions. The cutting forces are only affected by the feed rate, whereas the cutting temperature in contrast is affected by both spindle speed and feed rate. The temperature distribution indicates friction as the primary heat source, which is caused by the rubbing of the tool margins and the already cut chips over the borehole wall. Cutting forces were considerably higher when drilling animal cortical bone, in comparison to cortical test material. Drilling direction, and therewith anisotropy, appears to have a negligible effect on the cutting forces. The results suggest that this can be attributed to the osteons being cut at an angle rather than in purely axial or radial direction, as a result of a twist drill's point angle.

1. Introduction

The number of orthopaedic operations has been steadily increasing over the last few years. According to statistical data provided by the National Joint Registry in their 12th annual report [1], 226,871 operations were performed in the United Kingdom in 2014 alone, marking this year with a 9.3% increase compared to 2013. Academic and industrial research has been responding to this trend, by developing more effective surgical devices and efficient procedures, making the field of orthopaedics a major area of research. Performing the necessary validation procedures on these novel devices is a time-consuming and tedious process, mainly because surgical conditions (e.g. working with actual human bones with an intact vascular system) are hard to recreate. As the availability of live specimens (i.e. bone stock) is sparse, whatever sample size and quality required to be statistically relevant, reliable data is hard to obtain within a reasonable time-frame, before environmental deterioration like dehydration or biological decay takes effect and alters the specimens [2,3]. To somewhat mitigate these limitations, biomechanical test materials are used instead of genuine human tissues, not only because access to these is not constrained due to their commercial availability, but also because they maintain stable (bio-)mechanical properties.

While a number of researchers have investigated the physical and mechanical characteristics of these substitute materials (e.g. density, tensile and compressive strength) [4,5], there is still a lack of consistent information available regarding machining characteristics, i.e. cutting forces and cutting temperatures, which are crucial for the assessment of orthopaedic and other procedures involving bone and bone substitutes. Because one cannot derive reliable information on machining characteristics from the materials properties already available, the aim of this research was to fill the gap by providing information on the machining characteristics of commonly used biomechanical test materials and compare them to cadaveric animal specimens. In these experiments cutting forces (torque and feed force) and the resulting temperatures were measured for different kinds of bone and bone substitute materials, using discrete spindle speed and feed rate combinations. Cortical bone is highly anisotropic, due to the orientation of microscopic fibres called osteons, which are cylindrical stems of about 0.2–0.25 mm in diameter and 1–3 mm in length.

These are responsible for the high tensile and compressive strength of cortical bone tissue parallel to the main axis of the osteons [6,7]. As a result of the anisotropy of cortical bone, reaction forces during plastic deformation, i.e. fracture, seem to be also affected, so much so, that cutting forces in the case of single blade penetration were reported to exhibit a significant (up to 124%)

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Table 1
Materials and their mechanical properties used in the experiment [a][12], [b][13], [c][14], [d][2], [e][15].

Material	Density (g/cm^3)	Tensile strength (MPa)		Modulus of elasticity (GPa)	
		Axial (longitudinal)	Radial (traverse)	Axial (longitudinal)	Radial (traverse)
SawBones 1522-01	0.16 ± 10%[a]	2.1[a]		0.086[a]	
SawBones 1522-03	0.32 ± 10%[a]	5.6[a]		0.284[a]	
SawBones 1522-05	0.64 ± 10%[a]	19[a]		1[a]	
SawBones 3401-06	1.64 ± 2.5%[a]	106[a]	93[a]	16[a]	10[a]
Bovine cortical bone	1.92[b]	97.41[c]–113[d]	40.18 ± 9[c]	20.22c–25[d]	12.43[c]
Porcine cortical bone	1.96–2.38[e]	88 ± 1.5[d]	n/a	14.9[d]	n/a

increase in reaction force during radial cutting as compared to axial cutting [8]. Unfortunately, a comparison between axial and radial approach in drilling of cortical bone tissue has not been provided by the literature. As a consequence, tests on both radial and axial approach were included, in order to establish whether the drilling direction actually has an impact.

2. Materials and methods

2.1. Specimens

Four SawBones® biomechanical test materials with different densities were chosen for the experiment: a high porosity solid rigid polyurethane (PU) foam for simulating trabecular bone (SawBones 1522-01); two lower-porosity PU foams (SawBones 1522-03 and 05) for the more compact trabecular bone, and a high density epoxy and microfiber composite (SawBones 3401-06) for simulating human cortical bone. For testing animal specimens, bovine and porcine femur were chosen, as these are often used in experiments where a close resemblance to human bone structure is required [9–11]. An overview of the test materials and their corresponding properties can be found in Table 1. Unfortunately, mechanical properties for porcine bone in the radial direction could not be ascertained. Neither was it possible to obtain information on the thermal properties of the SawBones materials.

The cortical bone samples were acquired from a local butcher and were kept in a freezer at 15 °C for not more than 5 days. The specimens were prepared by slicing the diaphysis (mid-section) of the femur into disks of approximately 20 mm thickness, and milled flat using a machining centre, to ensure that the surfaces were parallel. Prior to the experiments the cortical bone samples were thawed in 25 °C water to minimise dehydration.

2.2. Tools

Drilling was the machining method chosen for this research, since it is an often practised material removal method in orthopaedic surgery [16] and, therefore, allows the results to be utilised in real life applications. In view of the width and thickness of the material layers in the available bone specimens, a hole diameter of 3 mm and hole depth 10 mm were selected. This diameter allowed for accommodating two or three 1 mm diameter thermocouple holes located at a distance of 1 mm from the test hole.

The drilling of deep holes was chosen in order to obtain a reasonable amount of data (due to long cycle times) and to test the effects of deep hole drilling, which often suffers from poor chip evacuation, leading to increased process temperatures. While research has been conducted on the optimal tool geometry in order to reduce cutting forces and process temperatures in bone drilling [e.g. 16–19], in this research the aim was not to minimise these effects, but to produce consistent cutting force signals of high enough magnitude to reliably assess the machinability of different materials. Walter A1276TFL tungsten carbide twist drills with a 40 helix angle, 140 point angle and wide chip flutes were selected for all cutting tests. Previous research—on materials other than bone (substitutes)—demonstrated that this type of drill geometry is well suited for drilling deep holes [20]. The use of tungsten carbide drills was expected to minimise the amount of tool wear, in order to reduce the variation in cutting forces due to a change in point geometry brought about by wear.

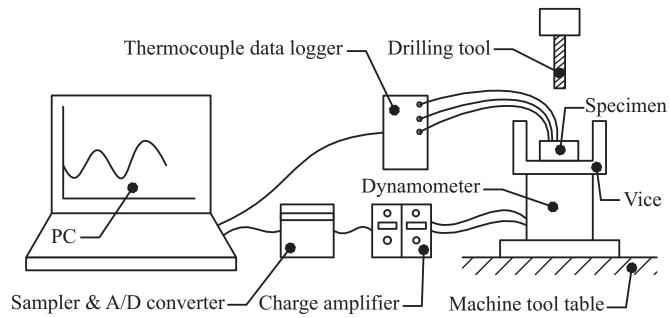

Fig. 1. Setup used to conduct experiments on a machining centre to record cutting forces (using a dynamometer and charge amplifier) and temperatures (using thermocouples) when drilling different types of SawBones as well as bovine and porcine bone samples.

2.3. Experimental apparatus and procedure

The experimental apparatus for the force measurement consisted of five major components: A Takisawa MAC-V2 machining centre, a Kistler 2-component dynamometer (type 9271A) with a custom-made clamping device mounted on top, a Kistler 2-channel charge amplifier (type 5001), analogue-to-digital (A/D) converter, and PC with LabVIEW 8.2 data acquisition software. The apparatus for the temperature measurement consisted of a PICO thermocouple data logger connected to the PC, running PicoLog data acquisition software, and 1 mm diameter Omega K-type thermocouples (type HKMQSS-IM100G-300). The entire setup is shown in Fig. 1.

Before drilling a test hole, in the case of SawBones and bovine bones, three thermocouple holes, with depths of 4, 6 and 8 mm, were drilled, see Fig. 2. In the case of porcine bone, due to the limited space available, only two thermocouple holes, with depths of 4 and 8 mm, were drilled. Following the preparation of the holes, the thermocouples were inserted, and once the temperatures had stabilised a single test hole with the given feed and spindle speed was drilled. Tests on radial bone drilling were performed on porcine cortical specimens with cutting parameter combinations of 700/0.12, 1000/0.15 and 1500/0.2 RPM/mm/rev in order to compare the effects of short, medium and long drilling cycle times. The cutting parameter window, see Table 2, was established based on information provided by Bertollo and Walsh [16] and parameters used by other researchers in their experiments [21–24].

Temperatures were not measured, because in radial drilling the bone's cortical layer was too thin to accommodate thermocouples