Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 70 (2015) 14 – 17

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

A miniature surgical drill using ultrasonic/sonic frequency vibration

Li Li, Andrew Mathieson, Margaret Lucas*

School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK

Abstract

A study is presented of a miniature ultrasonic surgical drill designed for bone biopsy, based on an ultrasonic/sonic drill which converts high frequency to low frequency vibrations through a freely vibrating mass between an ultrasonic transducer-horn and a drill bit. For conventional surgical drilling using a rotary drill or an ultrasonic drill, considerable power is required to penetrate into bone and the efficiency is low. However, for ultrasonic/sonic drilling, sufficient acoustic energy is accumulated and then released through each impact to achieve precise drilling with a lower power requirement. The ultrasonic/sonic drill was originally invented for rock drilling in low gravity environments. In this study it is incorporated in a miniature ultrasonic surgical drill and the effective impulse delivered to the bone is used to evaluate the drilling performance. To develop a miniature surgical device based on maximising the effective impulse, optimisation of the ultrasonic horn and free-mass is first demonstrated. The shape and dimensions of the ultrasonic horn and free-mass are determined through FEA, which focuses on maximising the post-collision velocity of the free-mass. Then, the entire dynamic stack constituting the surgical drill device is modelled as a mass-spring-damper system to analyse the dynamic behaviour. The numerical model is validated through experiments, using a prototype drill, which record the velocity of the free-mass and the drilling force. The results of the numerical models and experiments indicate this miniature ultrasonic surgical drill can deliver sufficient impulse to penetrate bone and form the basis of an ultrasonically activated bone biopsy device.

Peer-review under responsibility of the Scientific Committee of ICU 2015

Keywords: ultrasonic/sonic drill; bone drilling

1. Introduction

High power ultrasonics has been widely applied in many fields such as ultrasonic cleaning, joining and shaping of metals, and surgical devices. Power ultrasonic surgical devices have improved many aspects of bone drilling

* Corresponding author. Margaret Lucas.
E-mail address: Margaret.Lucas@glasgow.ac.uk

Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.009

procedures, such as higher accuracy, better preservation of delicate tissue and enhanced recovery rates. An ultrasonic drill tool typically has three main components: an ultrasonic transducer, an ultrasonic horn and a drill bit. The transducer is usually tuned to a relatively low ultrasonic frequency, in the region of 20 to 100 kHz, and employs a piezoceramic material to convert electrical energy to mechanical energy. A tapered ultrasonic horn is often connected to the transducer to provide amplitude gain, so that the small number of microns amplitude from the transducer can be increased to several tens of microns at the horn tip. The drill bit may be the front end of the horn or may be another tuned component connected to the horn. For either configuration, the whole device operates in a longitudinal mode of vibration at its tuned frequency. Compared to a conventional rotary drill, ultrasonic bone drills have the following advantages: low required applied force; less mechanical and thermal injury to nerves; and it is relatively easy to handle. However, for an ultrasonic surgical device, if the drilling target is hard tissue it can exhibit poor drilling performance. The reason for this is that the instantaneous pressure from the drill bit does not exceed the compressive strength of the bone during impact in each vibration cycle, and hence the drill does not progress (Harkness and Lucas (2010)). In order to generate sufficient instantaneous pressure, an ultrasonic/sonic drilling technology is employed to develop a miniature surgical drill device. This paper discusses the use of finite element analysis (FEA) and numerical methods to design and optimise a miniaturised drilling system before its manufacture.

2. Design and optimisation of the ultrasonic/sonic drill horn and free mass

Ultrasonic/sonic drilling was originally developed for rock drilling in low gravity environments (Bao et al. (2003)). In this methodology, a free mass, in the form of a small piece of metal, is placed between the ultrasonic transducer-horn and the drill bit as shown in Fig. 1(a). The ultrasonic horn impacts the free mass and transfers an impulse to the free mass. Then, the free mass moves forwards to hit the drill bit and delivers an impulse to the drill bit. Lastly, the free mass rebounds to finish one cycle. The drill bit delivers a considerable force to the target in a short time period for each impact. The area under the drilling force-time curve directly affects the rate of progress, determining the interval when the pressure applied by the drill bit exceeds the compressive strength of bone. Accordingly, it has been suggested that the impulse (area under the force-time curve) lying above the force threshold required to exceed the compressive strength of bone, is defined as the effective impulse, as explained in Fig. 1(b) (Harkness and Lucas (2010)), and can be considered as a design parameter to evaluate the drilling performance.

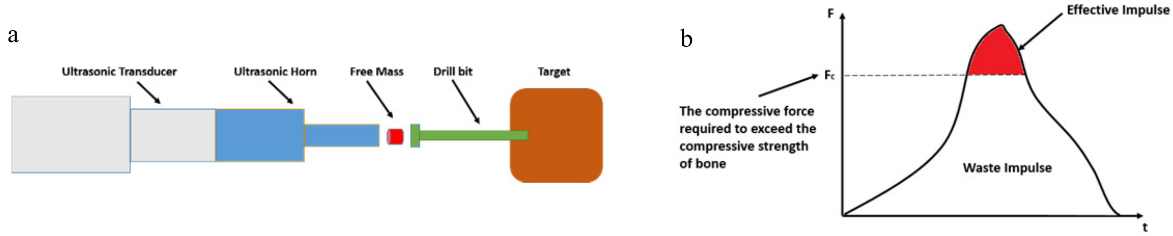

Fig. 1. (a) Schematic of the ultrasonic/sonic drill; (b) the definition of effective impulse.

For this drilling method, the horn is vibrating at an ultrasonic frequency while the free mass is vibrating at a sonic frequency. Compared to conventional ultrasonic drilling approaches that directly deliver the impulse to the bit, the advantage is that during the interval between two successive impacts the ultrasonic horn recovers its vibration amplitude and thus delivers a consistent impulse to the free mass and drill bit. The ultrasonic horn will have a significant influence on the dynamic characteristics of the surgical device. It is therefore necessary to select the most suitable horn shape to achieve a large momentum of the free mass and therefore high effective impulse. There are four shapes of ultrasonic horn that are usually used for ultrasonic drilling: stepped horn; stepped-exponential horn; exponential horn; and conical horn. The vibration amplitude gains of these horns are easily calculated but the effective mass is more difficult to determine. Therefore, four different shaped ultrasonic horns impacting the same free mass were modelled using a finite element analysis (FEA) package Abaqus. The four horns were tuned at the same frequency, about 50 kHz, as shown in Table 1, while the base diameter and tip diameter of the horns were kept constant. The velocity of the free mass after a single collision is used to evaluate the performance of the horns, and these are shown in Table 2.

Table 1. The length of different half-wavelength horns tuned at 50 kHz

	Calculation of horn length		Frequency (Hz)
	Analytical (mm)	FEA (mm)	
Stepped horn	50.27	49.70	49989
Stepped-exponential horn	64.45	64.62	50004
Exponential horn	54.94	59.94	49916
Conical horn	60.44	57.80	49975

Table 2. Velocity of the free mass after a single collision

Horn profile	Post-impact velocity (m/s)
Stepped horn	5.7
Stepped-exponential horn	4.9
Exponential horn	3.5
Conical horn	3.2

The free mass obtains the largest momentum from the stepped horn. The vibration gain of a stepped horn is determined by the horn's base and tip diameters, where a smaller horn tip diameter delivers a larger gain and therefore higher amplitude, but the effective mass is low and hence momentum is not maximised. Therefore, horn tip diameters varying from 3 to 15mm impacting the same free mass were modelled in Abaqus to evaluate the performance of the horns. A horn tip diameter of 5.5mm was selected based on the simulation results, because this resulted in transfer of the largest momentum to the free mass, while not exceeding the material fatigue limit. The free mass is placed between the ultrasonic transducer-horn and drill bit. The free mass imparts its momentum to the drill bit and therefore the mass and shape of the free mass directly determines the effective impulse and the device's lifespan. In this paper, the shape of the free mass is investigated and five different shapes of free mass are considered, as shown in Fig. 2(a).

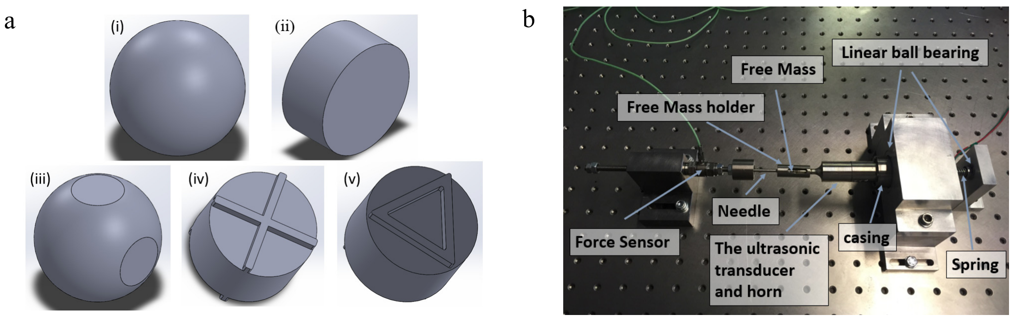

Fig. 2. (a) Different shapes of free mass; (b) a prototype of ultrasonic/sonic drilling system.

For a ball bearing shaped free mass (Fig. 2(a) (i)), there is a stress concentration due to the point contact and it is easy to damage the horn tip and free mass holder. A disc-shaped free mass (Fig. 2(a) (ii)) has a large contact area which has the advantage of reducing stress concentrations. However, its large contact area creates strong coupling with the horn, changing the vibrational characteristics of the system, making the drilling process difficult to start. The third type of free mass, a ball bearing with four flat faces (Fig. 2(a) (iii)), has the appropriate contact area for this system but is difficult to manufacture due to high toughness properties of the material. To avoid high stress concentrations, but to ensure that the system can readily vibrate, cylinders with a cross profile (Fig. 2(a) (iv)) or triangular profile (Fig. 2(a) (v)) on the top and bottom surfaces were adopted in this study.

3. Measurement of drilling force and mathematical model

To test the drilling force and evaluate the drilling performance, the experimental rig has been manufactured shown in Fig. 2 (b). A spring is located at the back of the rig to supply a preload and then keep the whole system together. The ultrasonic transducer-horn is fixed in a casing within two linear bearings. It can freely move forwards and backwards with minimal friction. The free mass holder and needle are manufactured as one part. A force transducer, which is in contact with the needle, is used to measure the drilling force and therefore the effective impulse can be calculated. A mathematical model has been built to simulate the entire dynamic stack, analyse the dynamic behaviour and optimise the ultrasonic/sonic drilling system. Each part of the dynamic stack is modelled as a mass-spring-damper (MSD). The drilling forces measured and calculated, from the experiment and simulation respectively, are shown in Fig. 3.

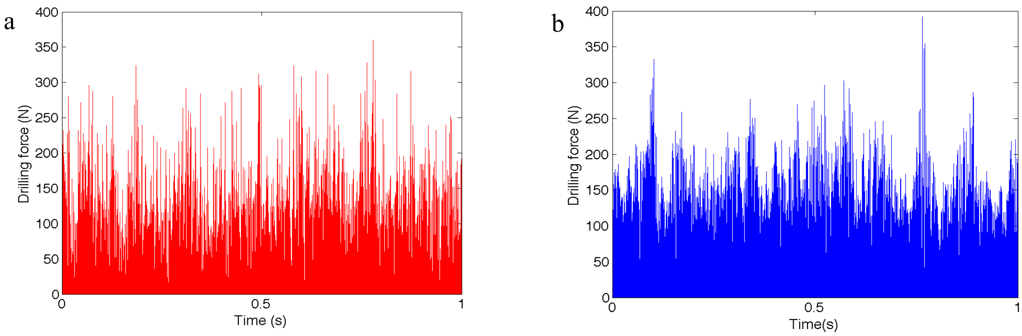

Fig. 3. (a) Drilling force measured from experiments; (b) Drilling force achieved from numerical model.

Fig. 3 indicates there is a good agreement between the experiment and simulation results. The peak pressure applied by the needle is 262 MPa. Bone tissue is normally drilled in the transverse direction and as the compressive strength of cortical bone in this direction is approximately 110 MPa (Li et al. (2013)), it is highly likely that the needle will penetrate bone.

4. Conclusion

A new ultrasonic surgical drill is proposed that is based on an ultrasonic/sonic drilling method. The initial experiments and numerical model indicate that the ultrasonic/sonic surgical drill can deliver sufficient impulse to penetrate bone. The MSD model will be further developed and used to optimise each dynamic component of the surgical drill to achieve maximum effective impulse.

5. Acknowledgement

This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) EP/K020013/1.

References

Bao, X., Bar-Cohen, Y., Chang, Z., Dolgin, B., Sherrit, S., Pal, D., Du, S., Peterson, T., 2003. Modeling and Computer Simulation of Ultrasonic/sonic Driller/corer (USDC). IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 50, 1147–60.

Harkness, P., Lucas, M., 2010. Optimization of the Horn, Free-Mass, and Support Architecture of an Ultrasonic Rock Coring System, AIAA Space 2010 Conference and Exposition. Anaheim, United States.

Li, S., Demirci, E., Silberschmidt, V.V., 2013. Variability and Anisotropy of Mechanical Behaviour of Cortical Bone in Tension and Compression, Journal of Mechanical Behavior of Biomedical Materials 21, 109-120.

MacBeath, A., 2006. Ultrasonic Bone Cutting. http://theses.gla.ac.uk/2220/ PhD Thesis, University of Glasgow.