Cleary, R. and Lucas, M. (2019) Comparison of Longitudinal-mode and Longitudinal-torsional Mode Ultrasonic Bone Biopsy Devices. In: 2018 IEEE International Ultrasonics Symposium (IUS), Kobe, Japan, 22-25 Oct 2018, ISBN 9781538634257 (doi:10.1109/ULTSYM.2018.8579919).

Comparison of longitudinal-mode and longitudinal-torsional mode ultrasonic bone biopsy devices

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Abstract—**Previous research by the authors has demonstrated the efficacy of an ultrasonic bone biopsy device that operates in a longitudinal (L) mode. Ultrasonic longitudinal-torsional (L-T) coupled vibration has proven successful in several applications including ultrasonic surgical devices. In this work, an L-mode ultrasonic bone biopsy device was geometrically modified by introducing helical slits to degenerate the longitudinal vibration into a composite L-T motion. The performance of the L-T biopsy needle device was then compared with the L-mode needle device based on their ability to penetrate animal bone samples. Finite element analysis was used to design the L-T needle. The depth and pitch of the helical slits were systematically modified in the FEA model with the aim of maximizing the achievable torsional displacement while ensuring sufficient frequency spacing between the L-T mode and the neighboring flexural modes. Experimental modal analysis (EMA) of the fabricated ultrasonic device was used to identify the modal parameters and validate the FEA model. Comparative penetration tests showed that to achieve penetration with the L-mode device, the operator was required to apply a slow backward and forward rotation as well as the small forward force, to maintain a forward motion and avoid imprinting of the needle tip. The resulting hole was slightly conical with some micro-damage on the hole surface. The L-T mode device, however, could penetrate the same animal bone sample only applying a small forward force, hence simplifying the procedure, increasing precision and resulting in a cylindrical, less damaged hole surface.**

Keywords— Ultrasonic Needle; Axial-Torsional Vibration; EMA; Bone Biopsy.

I. INTRODUCTION

A bone biopsy is an intrusive medical procedure used to diagnose an abnormality within the body. A small sample of bone is extracted and examined using microscopy to identify a bone disorder or establish the cause of discomfort. Generally, patients report moderate to severe pain levels for up to three to four days after a bone biopsy procedure is completed [1], [2]. For this procedure, the clinician usually uses a trephine needle and applies a large forward force, measured to be up to 400-600 N depending on the bone location. Additionally, lateral and twisting movements of the needle are required to penetrate the outer shell of the bone to retrieve the sample. Clinical studies have also found that the experience of the clinician significantly affects the pain levels experienced by the patient.

Previous work by the authors presented a class of ultrasonic bone biopsy needle capable of recovering a high-quality biopsy sample with very little force, just sufficient to physically couple the bone and needle and make forward progress [3], [4]. The current challenge is to improve the rate of progress through the cortical bone, simplify the procedure and reduce damage at the hole surface. This work proposes exciting a composite longitudinal-torsional (L-T) vibration of the needle to aid debris removal and avoid the needle tip imprinting and hence stalling in the bone.

L-T composite vibration has been applied across numerous ultrasonic applications including drilling and welding [5], [6]. Several different techniques have been examined to generate a composite mode of vibration. They can be generalised into two categories, achieved by incorporating tangentially polarised piezoelectric ceramics or by converting longitudinal vibration into torsional vibration. The design theory behind integrating tangentially poled piezoceramic is well established [7], [8]. High torsionality is achieved by designing the waveguide so that the longitudinal and torsional modes land on the same frequency. The technique is complex in terms of the mechanical design and electrical excitation [9]. It is also difficult to maintain resonance of both modes when driving under changing load conditions. Due to this, the preferred technique for this application will be the conversion of some of the longitudinal vibration into torsional vibration. The longitudinal vibration generated by an axially poled piezoceramic stack is degenerated into L-T vibration through geometric modifications to the waveguide [10-12].

Introducing torsional motion at the tip of surgical dissection instruments has been reported previously, showing to be a superior vibratory motion for the tip when cutting tissues [13-15]. This current study examines the potential of L-T motion for improved bone penetration in an ultrasonic bone biopsy needle. Two ultrasonic needles are realised which are tuned to vibrate in resonance to penetrate cortical bone. The first device is an axially vibrating Langevin transducer and needle configuration and the second is a variation of the first needle, altered to transform a portion the longitudinal motion into torsional motion.

II. METHOD

A. Device Design and Experimental Validation

As previously described by the authors [3], the tuned ultrasonic needle device was designed using Abaqus finite element analysis (FEA) (Dassault Systemes, Simulia). The device is a full-wavelength of the longitudinal mode, consisting of a half wavelength Langevin transducer and half wavelength needle insert. The L-T needle device was similarly designed in Abaqus FEA. For both devices, the geometry of the needle was selected to maximise the frequency spacing between the operational mode of vibration and surrounding parasitic modes of vibration. Once fabricated, experimental modal analysis (EMA) was performed to validate the modal parameters predicted using FEA. The displacement amplitudes of axial and tangential vibration were then measured at the operational frequency for a range of excitation levels, using a 3D laser Doppler vibrometer (Polytec CLV-3D).

B. *Penetration Tests*

Penetration tests were carried out to compare the L-T mode needle with the L mode needle. The time taken to penetrate 5 mm into a bone mimic material (Sawbone) was recorded and the penetration site was then analysed for damage. A biopsy was then performed on fresh ovine femur and the penetration site was scrutinised for damage.

III. DESIGN

A. *Longitudinal Mode Needle*

The ultrasonic bone biopsy needle is driven by a Langevin transducer with two PZT-8 (Ceramtec) piezoceramic rings, two copper electrodes and two Ti6Al4V end-masses. This half wavelength transducer is held in compression by an A2 steel bolt. A hollow Ti6Al4V needle is connected to the transducer via an M6 threaded stud, realising a full wavelength device. The needle device is tuned to the second longitudinal mode, L2, at 24.6 kHz, with the closest neighbouring modes being the third torsional mode, T3, at 21.8 kHz (an 11.2% frequency spacing) and the eighth bending mode, B8, at 27.2 kHz (a 10.5% frequency spacing).

B. *Longitudinal-Torsional Mode Needle*

Adopting the methodology of Al-Budairi et al [12], a mode degeneration configuration is designed which converts the axial vibration of the L mode into a combined L-T vibration. The conversion is achieved by introducing helical slots into the conical sections of the front mass and needle. FEA was used to optimise the depth and pitch of quarter-circle helical cuts. For a 6 mm cut, which represents a 34 mm cut along the axis of the front mass as shown Fig. 1, the twist angle was varied between 60º and 360º. The frequency of the L-T mode of vibration and surrounding modes is extracted as well as the torsionality of the L-T mode, representing tangential displacement as a percentage of the axial displacement. The results, shown in Fig. 2(a), suggest that as the twist angle increases, the frequency of the L-T and surrounding bending modes, B7 and B8, decrease while the torsional mode, T3, frequency does not change. The torsionality is greatest in the 180º - 240º range of helical cuts, reaching 24%. The 240º helical cut provided the maximum frequency spacing around the tuned L-T mode. The neighbouring modes, T3 and B8, are frequency separated by 8.9% and 10.2% respectively. The 240º helix cut was therefore chosen for the front mass and then extruded around the needle to further increase torsionality.

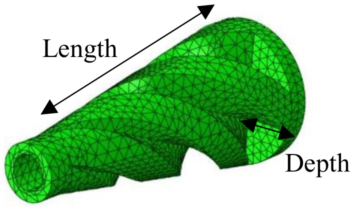


Fig. 1: Helical cut around the conical profile

Three depths of cuts, 1 mm, 1.5 mm and 2 mm, representing cuts along the length of the needle of 16 mm, 23 mm, 32 mm were investigated. To maximise the transmission of the torsional wave, the pitch of the needle section is configured to match that of the front mass. The results in Fig. 2(b) show that the torsionality increases as the depth of cut increases. For the deepest possible cut of 2 mm, the L-T mode was predicted as 23.8 kHz. T3 and B8 remained the closest neighbouring modes with frequency separations of 7.5% and 10.1% respectively. With good frequency spacing around the desired mode of vibration and a torsionality of 35% this design, with a 2 mm depth of cut, was chosen for manufacture of the L-T ultrasonic needle.

IV. RESULTS

A. *Experimental Modal Analysis Validation of FEA*

Once constructed, EMA was performed to validate each design. Fig. 3 shows the initial CAD models for the L mode and L-T mode needle devices. The FEA models are illustrated by the predicted modes of operation for the two needle devices. The EMA measured modes are shown with displacement measurement data, extracted from the measured frequency response functions, superimposed on a wire-frame measurement grid representation of the devices. The L mode needle device operates in resonance at 24.5 kHz with the T3 and B8 modes measured at 20.6 kHz and 26.2 kHz respectively. The L-T mode device was resonant at 23.6 kHz. In this case, the predicted B8 and T3 modes could not be identified as peaks in the frequency response, as the L-T mode dominated the response.

A strong correlation between the FEA predictions and EMA results was found for all the mode shapes and modal

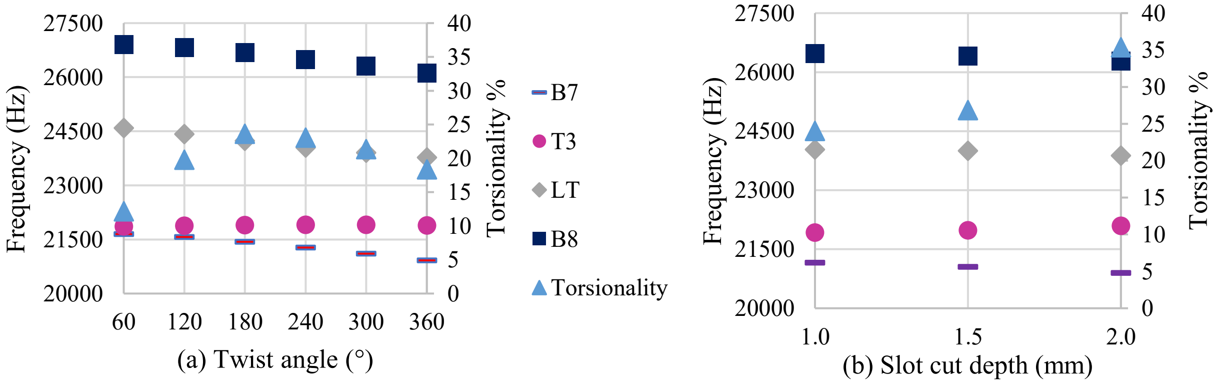


Fig. 2: Modes of vibration and torsionality for (a) 6 mm helix slots in front mass and (b) different needle slot cut depths

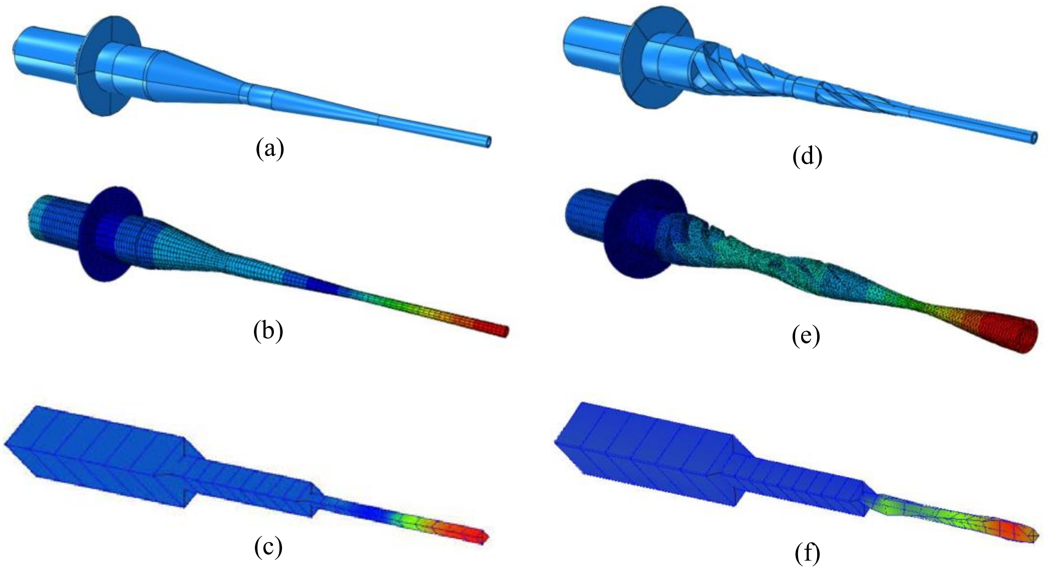


Fig. 3: L mode needle (a) CAD (b) FEA and (c) EMA. L-T mode needle (d) CAD (e) FEA (f) EMA

frequencies that could be identified from the measured frequency response spectra.

B. Driving the Needle at High Excitation Level

The tangential and longitudinal components of the displacement of the tip of the two ultrasonic needles were measured using the 3D laser vibrometer. The ultrasonic devices were driven under no-load conditions in air. The transducer was excited using a dedicated lab-based resonance driving and tracking system, controlled in LabVIEW and specifically created for testing high power low-frequency ultrasonic transducers.

Fig. 4 shows the displacement amplitude at the needle tip across a range of excitation levels of the transducer up to 40 V_{pp}. The longitudinal displacement of the L-T mode needle closely matched that of the L mode needle, demonstrating that longitudinal displacement is not lost by creating an L-T device, while gaining additional torsional response. For example, for an input voltage of 21.2 V_{pp}, the longitudinal displacement measured for both needles was 17 µm while a tangential displacement of 9 µm was additionally produced by the L-T needle. Over the range of excitation levels, the average torsionality was 44%, considerably higher than the FEA estimation.

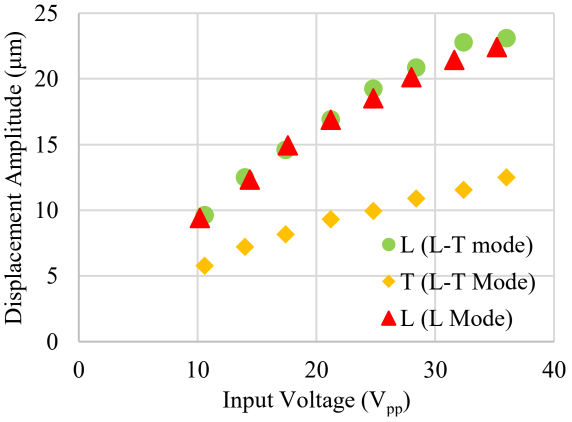


Fig. 4: Displacement at tip of L and L-T mode needles

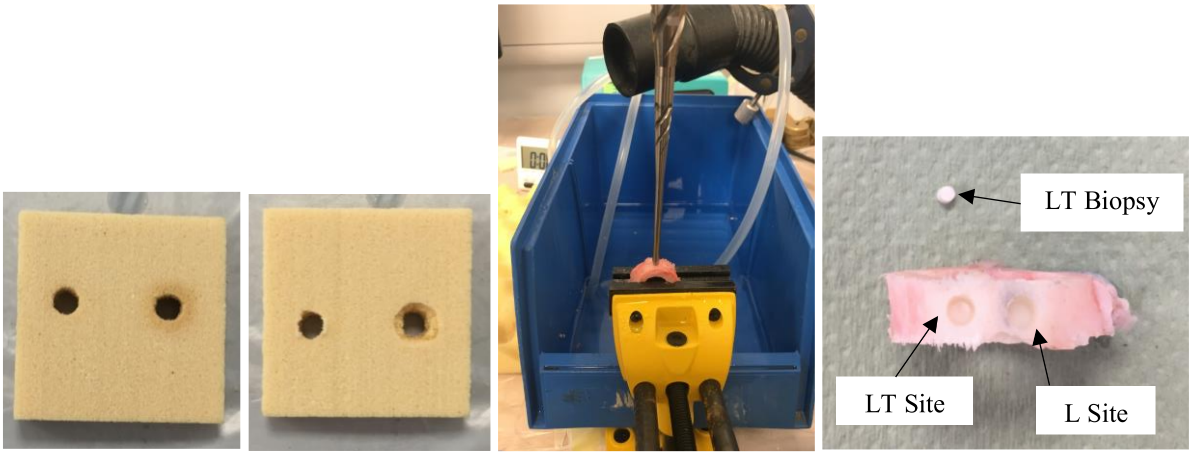
V. TESTING

Penetration tests were carried out to compare the performance of the L mode and L-T mode biopsy needle devices. Initially, the devices were driven by the resonance tracking system for penetration tests into the bone mimic material Sawbones, a polyurethane foam which offers similar mechanical properties to trabecular bone. The L-T device penetrated 5 mm in 38 s, while the L device penetrated 5 mm in 52 s. The L device stalled in the Sawbone sample unless the user added a slow backward and forward rotation of the device. In this case it was possible to fully breach the back wall of the sample. Some charring around the hole and damage on the rear penetrating wall of the sample could be seen as shown in Fig. 5(a). The L-T mode needle penetrated without stalling and with no requirement for an additional rotation motion. The penetration site was circular with considerably less micro-damage, as can be seen in the figure.

Fig. 5(b) shows the experimental set-up for penetrating into the diaphysis of an ovine femur. In these tests, both needle devices penetrated into the hard cortical bone and Fig. 5(c) shows the resulting penetration sites. Consistent with the Sawbone tests, the L-T mode device created a more circular hole, while the L mode device resulted in a wider and more irregularly shaped hole. The L-T mode device retrieved an intact core sample of bone, as shown in Fig. 5(c).

VI. CONCLUSION

The realisation of two configurations of a novel ultrasonic bone biopsy needle, L mode and L-T mode, has been presented. The measured displacement of each device under no-load conditions showed that a high degree of torsionality could be obtained for an L-T mode device without loss of longitudinal displacement. Penetration tests through the trabecular bone mimic material Sawbones and into cortical ovine femur bone showed that an additional slow rotational movement of the L mode needle by the operator was required to prevent imprinting and stalling. The introduction of torsional motion in the L-T needle meant that no additional



(a) (b) (c)

Fig.5 (a) Sawbone sites, front (left) and back (right), (b) experimental set-up for ovine femur tests, (c) ovine femur penetration sites and retrieved biopsy sample

rotation motion was required, simplifying the procedure. The L-t needle was faster and more precise, resulting in a highly circular and less damaged hole surface and an intact cylindrical biopsy sample. Future research will analyze the micro-damage and histology of the penetration sites and the quality of the biopsy samples.

ACKNOWLEDGMENT

This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) EP/K020013/1, with project partner Ethicon Inc.

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