INVESTIGATION INTO REMOTE ARTIFICIAL PALPATION IN MINIMALLY INVASIVE SURGERY (MIS)

H.T. Yeoh, G.A. Thomson

University of Dundee, Dundee, Scotland

h.t.yeoh@dundee.ac.uk, g.a.thomson@dundee.ac.uk

Abstract: Minimally invasive surgery offers many clinical advantages; it does however present its own difficulties. One such issue involves the inability for surgeons to be able to directly feel tissue for the presence of potentially cancerous lumps.

A number of approaches have been considered elsewhere and this paper reviews some of these. It will then discuss an alternative approach being developed at the University of Dundee. This approach uses both force and optical image analysis to attempt to determine the underlying nature of suspect tissue.

This paper presents a review of the work being carried out to create a clinically practical system. This is based on combining empirical work on both polymer phantoms and tissue seeded with mock tumours. This is supplemented by modelling techniques using finite element and conventional mechanical analysis.

From these results a proposal is put outlining how a future surgical tool using both imagery and force sensing will result.

Introduction

The minimally invasive surgical approach offers several advantages over traditional open surgery particularly with regard to recovery times. However it has been argued that the most significant disadvantage of minimally invasive surgery is that the surgeon does not have the opportunity to directly touch the tissue inside a patient's body to feel for tumours or lumps. The use of long rigid instruments to access the operation site in MIS means that it can be very difficult to accurately assess the tissue at the suspect area.

Similar research on palpation includes 'Robotic Surgical Assistants' developed by Howe and Peine [1] from the Division of Engineering and Applied Science, Harvard University. They have developed remote palpation instruments that convey contact information to the surgeon's fingertips from inside the patient's body. They were attempting to use for output to the surgeon what they called a "shape display", a row of 10 pins which allow the surgeon to place his finger over the top and feel the responses as he palpates internally. The system uses a series of 10 strips of shape memory alloy (SMA), which drives the pins upwards into the surgeon's finger. If the tactile sensor senses a less compressible material, for example a harder lump or tumour, then the pin which corresponds to that respective area on the tactile array of sensors, will be forced upwards into the surgeons finger by sending a current to the SMA wire.

This tactile sensation research they hope will allow the surgeon to feel what is occurring inside the body, via the tactile sensor and the shape display output. It is however felt that a simpler approach may have certain attractions and be easier to implement in a practical sense. Alternative designs, in addition to those carried out by the Harvard group, include the use of shape memory alloy [2], pneumatics [3], voice coils [4], piezoelectricity [5] and servomotors [6] have been proposed.

Another way to approach the palpation problem is by investigating the behaviour of tissue under palpation using theoretical and experiment work. Researchers have proposed that cancers are much stiffer than the surrounding tissue. In particular, Vacalebri [7] has designed a miniature robotic system to perform in vivo mechanical characterization of soft tissue. The tissue tester employs a stepper control using microstepping techniques, and a load cell to measure stiffness and the reaction force of tissue under tested tissues. Some investigators have used arrays of indentors [8-10], so that all indentations occur at one point in time. After deformation of the tissues, they recorded the force/displacement response. Several investigators took the images of the tissue at two different applied loads and compute a displacement field from them [11, 12]. There has also been extensive work on non-invasive measurement of the stiffness of tissue by measuring the propagation of elastic shear waves using magnetic resonance imaging [13].

There is surprisingly little available in the literature on tissues mechanical properties that would allow one to draw a conclusion to the nature of tissues directly from the estimated stiffness. Given this observation, in order to develop tractable mathematical models from which to extract material properties, most researchers have idealized the tissue to be isotropic and elastic [14-16] and incompressible [17].

To this end, research has been undertaken to develop a system based on a combination of modelling, coupled to image and force analysis of tissue undergoing palpation. It is intended this will ultimately provide feedback, realistic enough for the surgeons to feel they are diagnosing the tissue with a level of precision sufficient for reliable diagnosis.

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Materials and Methods

The aim of this project is to investigate whether the artificial palpation project is a feasible alternative to "real" palpation and will use the basic method of two Perspex plates acting as the fingers of the surgeon. The lower plate is driven in the horizontal plane, while the upper plate is loaded cyclically in the vertical direction. This thereby re-enacts the action a surgeon performs naturally with the fingers during palpation. In addition to this, this device also applies a light source through the palpation plates. This offers the surgeon enhanced ability to examine the palpated tissue through the transparent plates giving greater understanding of the size and nature of the tumours or lumps. Important to the system is an image capture system forming part of the palpation device. Imagery is taken during palpation and analysed using graphic imaging software to further aid in diagnosis.

A large scale test rig able to perform the cyclic palpation of tissue has been developed and is shown in figure 1. This however is not well suited to more fundamental research and for this more conventional tensile and compressive test equipment is used.

Figure 1: Large scale palpation test rig

At this stage of the research, the experimental focus has been on squeezing the tissue in the vertical direction to give an understanding of the behaviour of tissue under basic compressive loading conditions. The specimens used in this developmental stage are GelFlex as the bulk tissue coupled to various polymer "tumours" which provide differential mechanical properties with which to test the system. The experiment results were then compared with analytical results for isotropic tissue behaviour developed by Miller [17]. In compressing samples of this type it is crucial to determine the lateral behaviour of the tissue at the interface with the loading platens. In analysis this is generally assumed to be either non-slip or friction free, though the former is generally easier to approximate in practice. The method of attaching coarse sand paper as in Bilston's work [18] was applied to the experiment to present a non slip boundary condition.

For simplicity of analysis it was decided to simulate non-structural tissue, such as liver, as this can generally be regarded as exhibiting approximately isotropic properties provided a large enough sample is examined. The mock tissue sample used in this experiment is a cylindrical elastomer also known as GelFlex. GelFlex compounds are reversible gels which retain their degree of flexibility throughout their working life. Simple back to back compressive tests between GelFlex samples and geometrically identical lamb's liver samples showed similar stress strain properties.

GelFlex was melted at its pouring temperature (~140˚) and poured into cylindrical moulds, 26mm diameter, and 15mm high. The first specimen used for the experiment was plain without added material to simulate a mechanically isotropic tissue such as healthy liver. The second specimen featured an inclusion of an air bubble in the middle of it achieved through injection of air into the semi-cured GelFlex and designed to simulate trapped gas or air inside tissue. A 10mm diameter and 3mm height latex cylinder was implanted into the third specimen as latex, with its higher stiffness would act as lump hidden inside tissues. The approximate modulus of elasticity for GelFlex is 24kPa while latex is 183kPa so the ratio of Young's modulus of the latex and GelFlex is similar to the corresponding ratio of tumours and healthy tissue as proposed by Skovoroda [19]. Figure 2 shows a cross section of the trapped air sample used in this experiment while table 1 summarizes the specification of the test specimen.

Efforts were also made to generate a sample to simulate a fluidic cyst however, at this stage production of these was too inconsistent to draw meaningful results.

The specimens were then tested using a 4204 standard Instron testing machine (model 4464, Instron Corporation, MA, USA) fitted with a 1 kN load cell.

The top platen applied compression loading to the specimen and compressed the specimen to a height of 12mm from an original height of 15mm (0.8, height ratio) at a loading speed of 3mm/min.

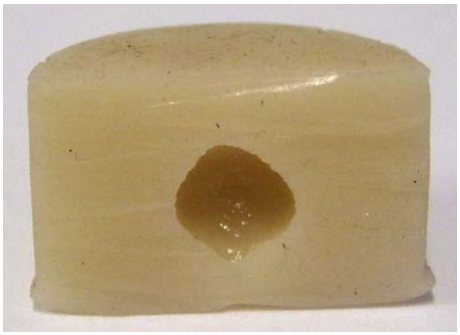

Figure 2: The slice of elastomer used in this experiment, showing gas trapped inside the GelFlex phantom

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Table 1: Specification of the test specimen

Specimen	Composition	Simulate
1	Plain GelFlex	Plain Tissue
2	GelFlex + Bubble	Trapped gas
3	GelFlex + Latex	Hard lump

In addition to results directly obtained from the compressive test machine, digital cameras were set up to monitor the deformation of the samples both axially with the loading direction and orthogonal to this.

Results

The results obtained from the artificial palpation instrument were obtained through numerous tests. Figure 3 shows aggregated nominal stress and nominal strain for the three specimen phantom types. From the data obtained, specimen 3, GelFlex with latex, as might be expected, is seen to be stiffest, followed by plain GelFlex while specimen 2, GelFlex with an air bubble is extremely soft. The importance of the squeezing and compressing movements of the vertical axis can be directly linked to the compressibility of the tissue being examined. In its simplest form this could be approximated to simple variable stiffness springs in series and parallel however in reality a more complex model would be required to allow for lateral movement of soft tissue being pushed around a harder tumour when loaded in compression.

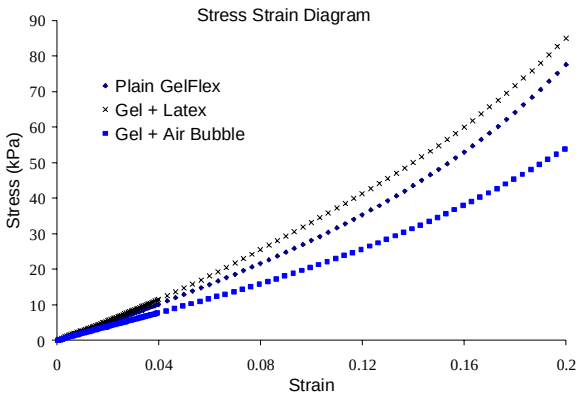

Figure 3: The stress and strain curve for the experiment

These results were further analysed using both optical methods and finite element analysis.

Figure 4 shows an image taken axially of a plain GelFlex specimen under compression. The inner circle representing the specimen base and the outer area was the bulging area of the specimen under compression. In practice it is unlikely that a measurable difference in specimen diameter change will be observable between the different tissue types and this was borne out by the experimental work.

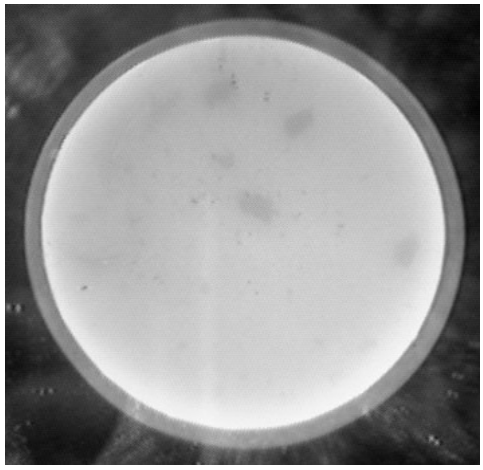

Figure 4: The change of geometry after simple compression test

In contrast it is however felt that side on analysis of the deformed specimens may be more productive. Figure 5 and 6 shows the deformation of a specimen and an analogous stress result from ANSYS finite element analysis. In simple compression the results bear out the findings of Miller [17], while the FE analysis also confirms the ability to discriminate between tissue types using the compressive tests as shown in figure 7.

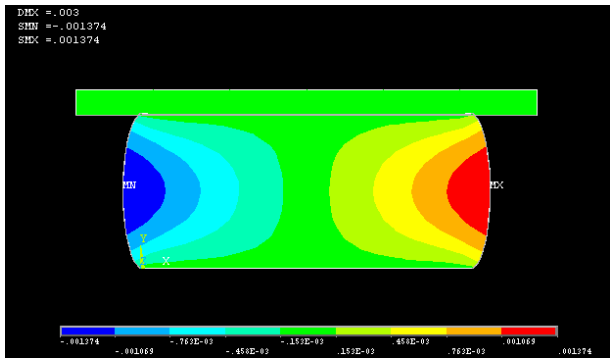

Figure 5: The analysis on degree of movement in lateral direction from ANSYS

Figure 6: Photo taken from the side view of pure GelFlex specimen after compression

It is however thought that a key area for analysis in relation to the imagery approach will come by loading the specimen in shear.

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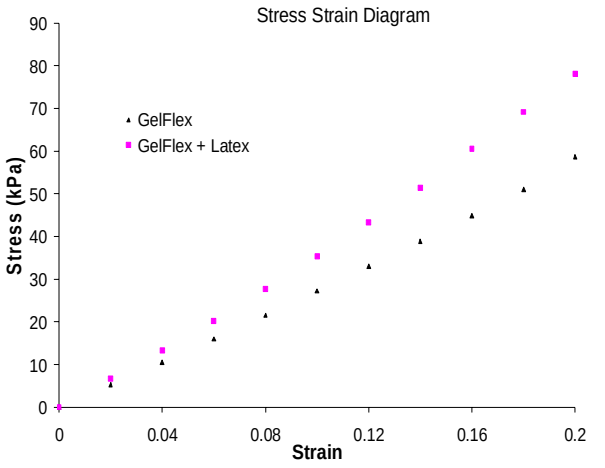

Figure 7: The analytical calculation on stress for the test

Discussion

The results obtained by this project are encouraging and indicate that a future intelligent instrument should be able to differentiate between normal tissue and tissue with anomalies. The experimental results also appear to tie in well with models derived from analysis elsewhere and with FEA work carried out as part of the trials. Results were obtained through numerous tests and these show that this instrument has the ultimate potential to offer a reliable alternative to direct physical palpation.

The optical view of the changing geometry of the elastomer under compression from the side was unable to detect any differences in the physical properties of the phantoms. However these can be distinguished by shearing analysis as shown in figure 8 which will be discussed in a future paper.

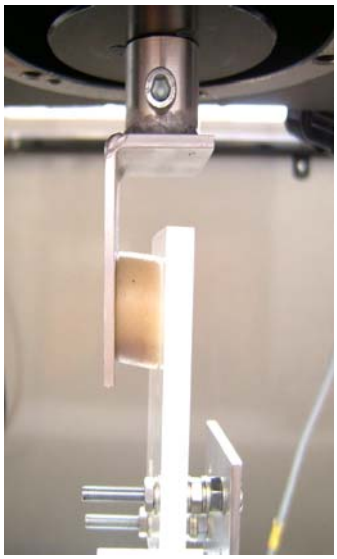

Figure 8: Shearing on 'Plain Tissue'

In the mean time with the help of a high intensity light source, it looks possible to scrutinize the tissue as the light can help differentiate the properties of the tissue. This was shown in figure 9, the darker sport in the centre of the area was latex.

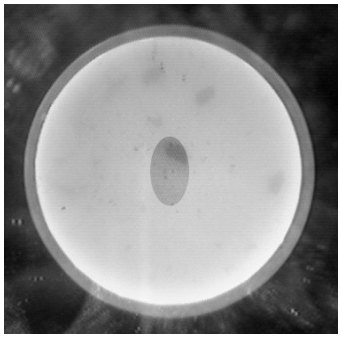

Figure 9: Photo taken after compression on specimen 3

While work to date has largely focussed on the use of artificial phantoms work has been carried out on real tissue, lamb's liver was used in benchmarking the compression test (Figure 10). These will offer potentially more realistic analysis however for practical reasons it is felt that artificial phantoms samples are still likely to be used during most of the development work.

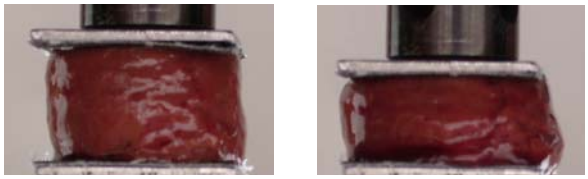

Figure 10: Compression test (before and after) on liver

Results obtained from the experiment look promising and prove this intelligent palpation instrument is able to identify lumps quickly and accurately. However to enhance the instrument's accuracy, the second stage work on this project which will focus on applying shearing force to the tissue have been plan.

Conclusion

At present, this research provides some of the building blocks from which an intelligent palpation instrument could be developed, allowing realistic palpation of artificial tissue, through force sensing, proper lighting, motion control and graphic imaging software.

Further investigation into the motion of the palpation plates will focus on the behaviour of tissue under combined shear and direct loading and into system improvements through light source manipulation

Further research will also focus on how best to convert the raw data from the force and optical sensors to a user friendly format to give the surgeon a better and clearer understanding of the size, location of the tumour. It is currently proposed that this will couple processed sensor and optical data to a knowledge base via a fuzzy logic engine, and detail development of this will be undertaken in conjunction with clinicians.

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Commercial development of this work will require minimisation of the device in addition to ensuring both physical and analytical integrity of the final product. It is felt however that if this can be done a reliable method will be available to MIS surgeons to help at least in some way compensate for loss of direct tissue contact.

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