Evaluation of Force Feedback Requirements for Minimally Invasive Lung Tumour Localization

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***Abstract*—Minimally invasive surgery is a technique that provides numerous benefits to the patient, but presents challenges to the surgeon in that dexterity, hand-eye coordination and haptic perception are compromised. Robot-assisted minimally invasive approaches have addressed the problems of dexterity and coordination; however, the lack of kinesthetic and tactile feedback remains a significant drawback. Despite many advances in this area, little is currently known about what level of feedback performance is adequate to allow the surgeon to palpate tissue to detect an underlying tumour. This paper describes experiments that were conducted on *ex-vivo* porcine lung, using artificial tumours, to elucidate one measure of sensor performance required to detect the presence of a tumour. The results indicate that a force-sensitive probe with a sensing range of 0 to 10 N and a resolution of 0.01 N would allow a tumour to be localized via palpation using kinesthetic feedback.**

I. Introduction

Minimally invasive surgery (MIS) is characterized by the use of long, slender instruments to perform surgical procedures through small incisions, 5–12 mm in diameter. This approach presents considerable advantages over conventional open surgery in that tissue trauma is minimized, reducing the risk of infection, length of postoperative recovery, and associated costs. MIS also introduces significant drawbacks such as reduced dexterity and haptic feedback, and the reversal of lateral tool tip movements due to the instruments pivoting about the insertion point. Current surgical robot systems, such as the da Vinci® from Intuitive Surgical Inc., eliminate the reversed hand motion at the surgeon's interface; improve dexterity, allowing direct hand-eye coordination to be re-established [1]; and present other advantages, such as tremor filtering and motion scaling. Nevertheless, a commercial solution to the issue of force feedback, able to provide the surgeon with haptic information has not yet been developed. The term haptic, meaning the sense of touch, can be subdivided into two distinct modes: tactile feedback, which includes the sensation of shapes and textures [2], or distributed properties acting on the contact surface; and kinesthetic information, which encompasses movements and bulk forces acting at the point of contact and at the joints. Reproduction of tactile [2]–[8] and kinesthetic [9]–[14] senses for the purposes of MIS have been the subject of considerable research.

In conventional open thoracic surgery for lung tumour resection, one of the surgeons' most effective intra-operative means of identifying the presence of disease or pathology is the ability to directly palpate the tissue, allowing a qualitative assessment of the mechanical properties of the tissue. Since many cancerous lung tumours are stiffer than the surrounding tissue, they can be easily identified as hard nodules when palpated. However, direct palpation of the tissue is not possible in MIS. Furthermore, the surgeon's ability to use the MIS instruments to identify anatomical anomalies is compromised by the friction and moments introduced by the interactions between the instrument, the trocar, and the cavity wall.

Imaging techniques such as MRI and CT scanning are invaluable for identifying lesions pre-operatively, but are generally not available for intra-operative use. Since the lung is deflated during surgery, and can move within the thoracic cavity, the pre-operative images cannot be readily used to pinpoint the location of the tumour during surgery.

As an alternative, laparoscopic ultrasound (if available) can be used to identify tumours during MIS. This approach is difficult to use in lung tissue due to artifacts caused by residual air, and proves to be nearly impossible when trying to localize small tumours (<1 cm diameter), precluding the use of an MIS approach in some cases. This has motivated the design and development of MIS instruments and sensors that provide haptic feedback to the clinician. Researchers have developed both grasper and probe type tactile feedback systems, in addition to kinesthetic feedback devices, the majority of which are intended for use with grasper type instruments to monitor tissue manipulation forces. For lung

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tumour localization, graspers may prove to be unfeasible due to their inability to reach the thickest regions of the lobes.

The design of a sensor system for use in MIS presents several challenges in that the sensor must meet demanding size constraints, withstand temperature variations, address issues of sterilization, and use biocompatible materials, while achieving appropriate performance in terms of resolution and sensing range. Interestingly, little is currently known about the force-deformation relationships for different target anatomies as it pertains to the identification of lesions within lung tissue. In [15], a finite element model is used to model the stress profile along the surface of a probe in the presence of an underlying tumour with the goal of using measured pressure variations to determine the size, stiffness, location and depth of a tumour. [16]–[18] present *in vivo*, *in situ* and *ex vivo* methods of measuring tissue stiffness and compliance for the purpose of developing more realistic models for haptic simulators and to aid in instrument design.

This research presents the differences in the force-deformation relationship that can be expected when comparing excised lung tissue which is intact, to that containing an artificial tumour. It should be noted that the major constraints presented by actual MIS procedures, such as trocar friction, tool access angles and remote centres of motion are not considered in these experiments. Nonetheless, it is expected that this information will prove useful in developing robotic or handheld systems that use kinesthetic and possibly tactile feedback for the task of lung tumour localization during MIS. To the best of our knowledge, no similar research has been conducted using animal tissue, specifically porcine lung.

II. METHODS

The objective of this project is to evaluate the sensor performance that is necessary to detect and localize small tumours within lung tissue. For this purpose, the force feedback measured by an instrumented probe is compared when palpating *ex-vivo* lung that is intact to that containing an artificial tumour. The hypothesis is that the force measured when palpating an artificially diseased lung will be higher than that measured when palpating intact lung tissue. This approach was shown by [19] to be feasible for detecting stiff materials embedded in soft foam.

A. Experimental Set-up

An aluminum probe, approximately 50 cm long with a 9 mm diameter, was connected to a Gamma, 6 degree-of-freedom Force-Torque Sensor from ATI Industrial Automation (calibrated for a 0 to 100 N axial force range, with a resolution of 0.003 N) which was mounted on a Mitsubishi PA10-7C robot, Fig 1. To assess the impact of different probes, four probe tip geometries were tested. Their descriptions are listed in Table I.

TABLE I
DESCRIPTION OF PROBE TIP GEOMETRIES.

Probe	Face Profile	Dimensions
A	Flat, circular	9 mm diameter
B	Flat, rectangular	10 mm × 30 mm
C	Flat, circular	3 mm diameter
D	Hemispherical, circular	9 mm diameter

B. Artificial Tumours

Several methods of simulating tumours within the lung tissue were considered. Initially, small volumes of silicone were placed under the lungs, or inserted into the lung parenchyma through small incisions. Both approaches produced a less than ideal model due to the lack of compliant tissue beneath the artificial lesion, or the ability of the silicone to move freely within the incision, respectively. Suturing the silicone in place was not favourable due to the compression of the surrounding tissue.

In an attempt to avoid both lateral movement and suturing, an alternative method mounted the tumour on a flexible mesh which was suspended between two halves of a lung which had been cut along the coronal plane. Validation tests were conducted, measuring the force feedback before and after the cut was made, as well as with the mesh present, with controls measured at neighbouring points. These tests revealed that simply cutting the lung produced an unacceptable change in the force-deformation behavior of the lung tissue.

The method adopted for this study was to inject material into intact *ex-vivo* lung to simulate a tumour. Sigma Gelrite Gellan Gum (agar) was mixed in a ratio of 7.5 g per 225 mL of water, boiled, and injected into the lung prior to solidification. Preliminary test tumours using 0.5 mL of agar (equal to the volume of a 1 cm diameter sphere) were too

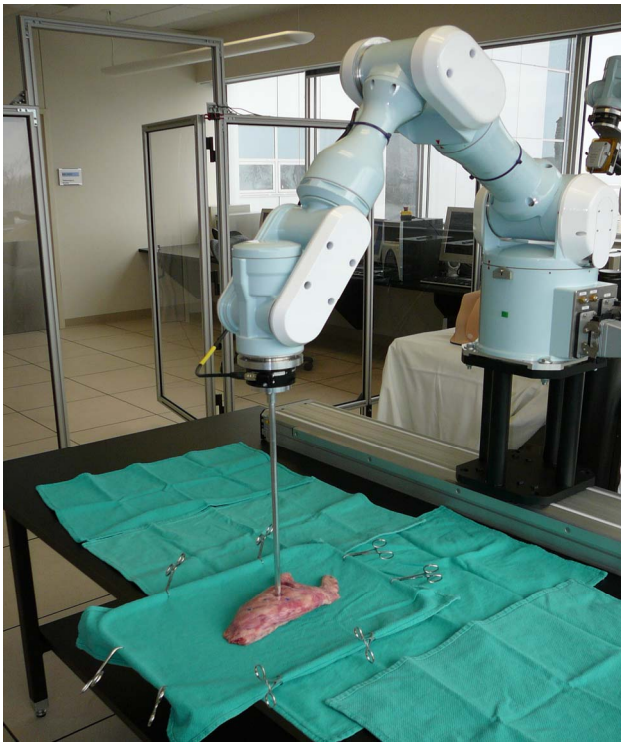

Fig. 1. The Mitsubishi PA10-7C robot outfitted with a force sensor and probe palpating *ex-vivo* porcine lung.

small due to the tumours forming in abnormal shapes and leakage of the liquid agar through the needle punctures; therefore, approximately 1.5 mL of agar was injected for each tumour during actual testing. Fig. 2 shows the tumours that were excised from the lungs once testing was completed. Testing was completed within two days of the agar being injected, and within one week post-mortem. When not in use, the lungs were wrapped in surgical towels saturated in saline solution, sealed in separate plastic bags and refrigerated. Note that, the effect of lung tissue autolysis was not considered in this study.

Experience in thoracic surgery suggests that the feel of common lung malignancies can be qualitatively described as ranging from the stiffness of a grape to that of a rock. Examination by an experienced thoracic surgeon indicated that the feel of the simulated tumours was within the range of tumours commonly encountered in the operating room. Similarly in [10], experienced surgeons were asked to qualitatively validate that hydrogel materials used as artificial liver tissue provided a realistic representation of actual healthy tissue as well as tumour tissue.

C. *Experimental Approach*

Two possible options to evaluate the force/deformation relationship were considered: the probe could palpate to a constant depth and record the force, or advance until a specific force was encountered and record the depth. This problem has been analyzed in [19] using mathematical models and experimentation. It was found that the constant depth scheme would show greater sensitivity in visco-elastic materials with non-linear deformation curves. Therefore, the constant palpation depth approach was adopted for these experiments.

The PA10-7C robot was programmed to move toward the surface of the lung (parallel to the long axis of the probe) in 1 mm increments until 0.1 N was measured in the axial direction, indicating that the probe was at the surface of the lung. Once this threshold value was met, continuous force measurements were taken for a total of 9 seconds as the probe advanced to the appropriate palpation depth: 5 mm, 7 mm or 9 mm, and then held stationary. The probe then retracted and moved 35 mm towards the inferior tip of the lower lobe and the process was repeated. Preliminary tests with the artificial tumours revealed that the tumour would occasionally crack when palpated at depths beyond 10 mm.

Three points were sampled with each probe (1 probe per lung). Pre-planning ensured that these points were not directly above any major anatomical structure, such as a major bronchial branch. The measurement process was repeated three times at each location and at each depth for a total of 27 measurements per lung, 9 at each depth.

After all intact lung measurements were completed, the test sites were marked using permanent marker and agar was injected at the same sites. Once the agar solidified, 22 gauge syringe needles were inserted into the sites as markers, and the lungs were imaged to verify that the artificial tumour had formed in the correct location. Radiographs of the lungs (Fig. 3) revealed that several of the tumours had not formed directly below the intended sites. Therefore, each tumour was carefully located through direct palpation prior to repeating the measurement process for each artificial tumour.

It must be noted that repeated palpation may alter the tissue response — an effect known as pre-conditioning. Pre-conditioning involves subjecting the sample to repetitive strain cycles to attain a steady-state stiffness behavior and constant hysteresis in successive cycles [17]. Since surgeons wouldn't pre-condition tissue before palpating, the number of samples taken at each site, and recovery time (>30 s) were chosen to limit preconditioning. In [17], tissues did not reach a pre-conditioned state within 10 cycles of up to 20 N. Since

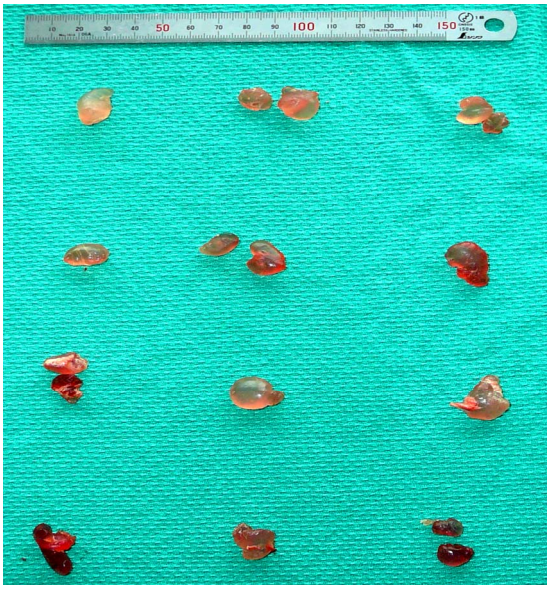

Fig. 2. Excised artificial (agar) tumours. From left to right: Location 1 to 3. From top to bottom: Probes A to D. (Note, some of the tumours broke during removal. All fragments are included in the figure.) The major scale increments are 1 cm.

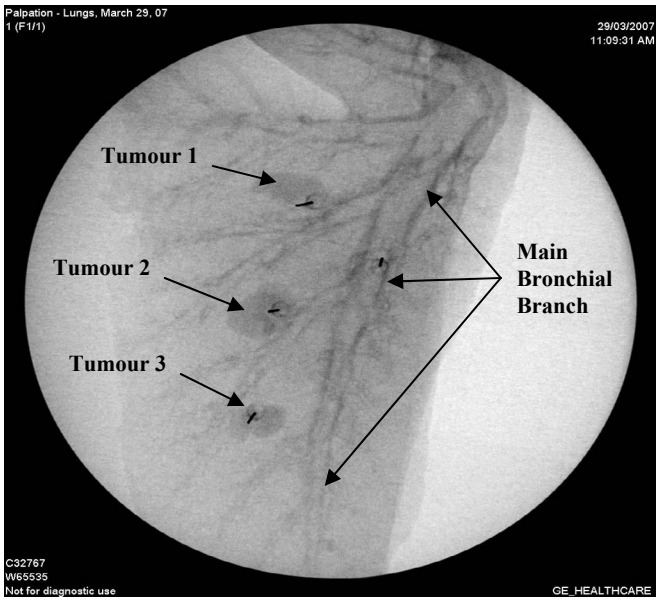

Fig. 3. Digital radiograph of a porcine lung taken after three artificial tumours had been injected. Syringe needles (solid black marks in image) were used to mark the injection site of the agar. The needle in the main bronchial branch was used to mark the bronchial location for another study.

each site was palpated to the maximum depth only 6 times (3 times for both intact and artificially diseased tissue), and the applied force was less than 2 N, it was concluded that little pre-conditioning occurred.

D. Signal Sampling and Processing

Continuous measurements were collected during palpation at 65 Hz and subsequently filtered using a second order Butterworth filter with a 2 Hz cutoff frequency. Comparing raw and filtered data (Fig. 4) shows that the filtered data is representative of the actual signal. The time response plots showed a characteristic peak at ~1.2 s followed by a decreasing signal which approaches a constant measurement at ~7.7 s. Analysis of the results was considered at both the peak time and after the signal had settled.

III. RESULTS

The data were examined using unpaired *t*-tests to compare the difference in the average forces at all locations collected before and after the tumours were inserted and using paired *t*-tests, pairing common locations taken before and after the tumours were injected. In both cases, results from different probe geometries and depths were discrete.

Normal Probability Plots constructed using measurements from previous experiments (n = 15) indicated that the assumption of a normally distributed population implied by the *t*-test was appropriate. The Welch's Approximate *t* approach was used since an assumption of equal variances could not be made [20].

A. Measuring Peak vs. Settled Forces

Since the tissue response decays over time with constant strain, it is important to compare the force reflections from intact or artificially diseased lungs at the same point of decay.

Fig. 5 compares the peak force to the settled force according to (1), where F_{TP} is the average force measured with a tumour present, and F_{TA} is the average force when a tumour was absent.

$$F = (F_{TP} - F_{TA})_{peak} - (F_{TP} - F_{TA})_{settled.} \quad (1)$$

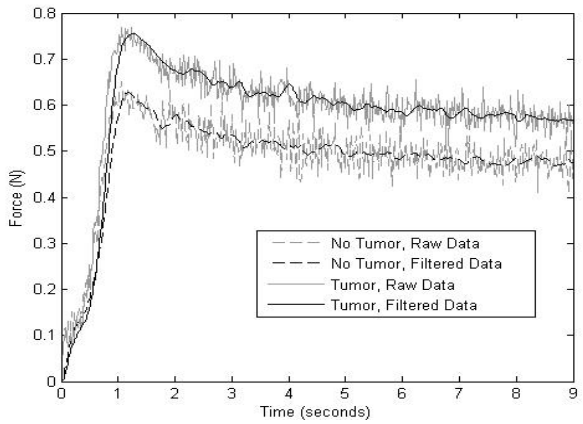

Fig. 4. Force vs. Time plots for a 9 mm palpation before and after an agar tumour was injected. Both raw and filtered data are shown.

This suggests that greater sensitivity can be attained by comparing the peak values rather than the settled values, in the majority of cases. For this reason, the remainder of the paper will focus on the variations associated with the peak force measurements.

B. Absolute Force Measurements

In order to appropriately specify sensor performance, the necessary sensing range must be known. Fig. 6 depicts the mean of the absolute force measurements recorded at each location, depth and probe type in the presence of an artificial tumour.

C. Discriminating Tumours on a Point-by-Point Basis

Fig. 7 shows the results of the Two-Sided Student's *t*-Tests that were used to compare the mean of the samples for each given condition (i.e., same depth and probe geometry) and location using the peak values. The *t*-test compared the hypotheses H_0: $\mu_1 = \mu_2$ and H_1: $\mu_1 \neq \mu_2$. Where μ_1 and μ_2 are the means of the samples taken before and after the artificial tumour was injected. The whiskers in Fig. 7 show the 95% confidence interval, indicating that the null hypothesis could *not* be rejected in 30% of the comparisons.

D. Paired t-tests with Common Probe Geometries

If it is assumed that the mean of the samples taken at any one location with a specific depth and probe is representative of that specific condition, the data can be examined using a paired *t*-test, pairing the means of a particular point, depth, and probe from before and after the tumour was implanted. The results of this analysis are given for peak measurements in Fig. 8. Again, the 95% confidence interval is indicated.

These results show that the variation in force reflection associated with the presence of a tumour is quite consistent across Probes A, B, and C, all of which share the common characteristic of a flat face. Probe D, with a hemispherical face, was not only inconsistent with the other three probes, but it also produced the smallest variations associated with the presence of a tumour. Results from Probes B and C both have p-values < 0.05, regardless of the depth of palpation.

IV. DISCUSSION

The independent *t*-tests (Fig. 7) indicate a strong trend of increasing force in the presence of a tumour. However, the 95% confidence intervals indicate that a statistically-significant conclusion cannot be made from this treatment; this is likely due to the small sample size which was adopted to avoid pre-conditioning. Additionally, some data do not follow the expected trend, namely, Location 1 for Probes A and D. Location 1, on all four lungs, was close to the thickest part of the lung and since the tumours were injected at approximately the mid-depth of the tissue, the tumours at this location may have been deeper than at any other site. This makes locating the tumour, even by manual palpation, quite difficult.

The pairwise comparisons shown in Fig. 8 provide a very positive statistic for Probes B and C, even with a sample size of n = 3. They indicate that there is a detectable difference

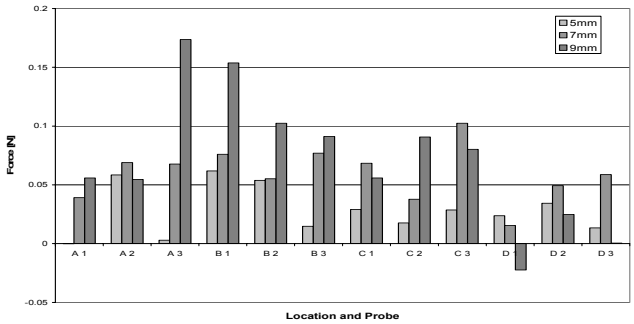

Fig. 5. The difference between the mean peak force increases due to the presence of a tumour; and that of the settled response. 'A1' indicates Probe A, Location 1.

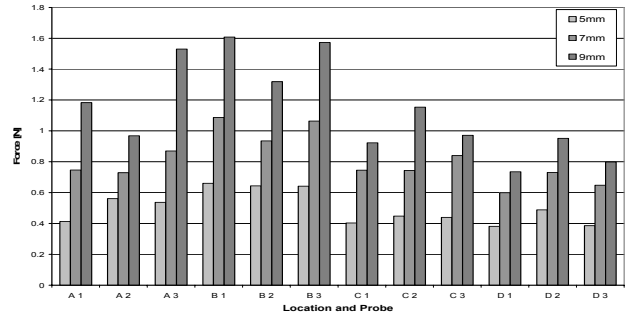

Fig. 6. Mean peak force encountered at each location with each probe, when palpating a tumour.

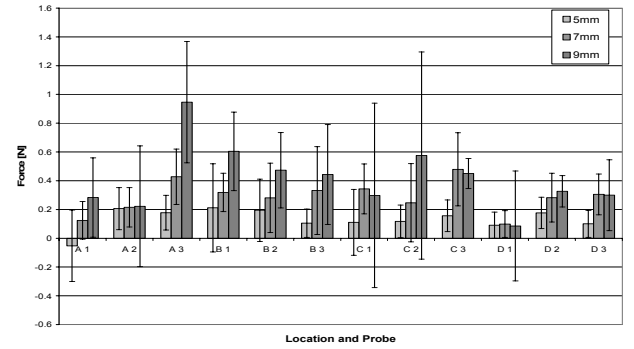

Fig. 7. Difference between mean *peak* forces measured before and after the artificial tumour was injected.

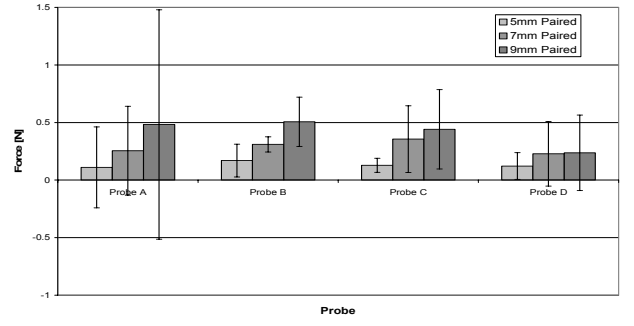

Fig. 8. Results from paired *t*-tests showing the average difference between peak measurements taken with and without tumours. The 95% confidence interval calculated using standard error is included.

between the force measured when palpating lung tissue in the presence or absence of an agar tumour. This supports the assumption that even with shallow palpation, force feedback alone could be used to probe the lung to distinguish an underlying tumour. However, the detectable difference is quite small, ranging from about 0.1 to 0.5 N when palpating from 5 to 9 mm depth using a probe with a flat face. Further investigation using the pairwise method, with a much larger sample size and a multitude of lung samples would better assess the effectiveness of force-based tumour localization.

The issue of tissue damage should be addressed when considering the use of a tactile probe for locating a tumour. In these experiments, the data indicate that probing deeper makes the differentiation of artificially diseased tissue more apparent. However, this increases the applied force and not only increases the risk of damage to the healthy tissue, but it may result in the rupture of some tumours, thereby leading to spread of the disease. Developing an understanding of the maximum safe probing force would benefit the development of MIS tactile sensors. Nevertheless, since current practice is to probe the tissue using non-sensorized MIS instruments to find visual or limited tactile cues that may indicate the presence of a tumour, any form of force feedback would likely serve to limit the inadvertent application of excess force.

The comparison of peak to settled force response (Fig. 4) reveals that the difference tends to be more pronounced between the peak forces. This would suggest that an instrumented palpation system should compare the peak forces recorded. Examination of the peak force is further supported by [17] which notes that the rate of stress decay, with constant strain, was greater for *in-situ* (post-mortem) samples than for *in-vivo* samples. However, because the peak force is dependent on the visco-elastic nature of the lung tissue, the speed of the palpation probe will have an effect. This suggests a robotic approach, through which variables such as approach speed and palpation depth can be controlled.

To avoid quantization errors, a sensor resolution that is one order-of-magnitude less than the smallest variation to be discerned is desirable. This indicates that the appropriate sensor resolution required to use kinesthetic feedback for lung tumour localization is on the order of 0.01 to 0.05 N. Therefore, a resolution of 0.01 N at the tip of the instrument is an appropriate target. However, since palpating the lung to a depth of 9 mm or more is common during actual finger palpation, a resolution as large as 0.05 N may still be acceptable.

Sensing range is also an important consideration in sensor performance. Given that peak forces of 1.6 N were encountered when palpating to 9 mm, it would be reasonable to define the required sensing range to be the next highest order of magnitude, or 10 N. This would also facilitate deeper palpation of the tissue, if required.

A sensing range of 0 to 10 N with a resolution of 0.01 N suggests a minimum dynamic range of 1000:1. This range corresponds to the range of 0.1 to 11 N reported in [21] to be commonly accepted for sensor performance in medical applications. However, no indication of the necessary resolution was offered.

These performance requirements indicate that some previously developed approaches to force feedback such as [1] and [9] may be adequate for tumour localization, whereas others such as [22] may have inadequate sensing resolution.

It is interesting to note that the probes with the largest and smallest contact area exhibited the greatest sensitivity and had the smallest deviation between samples. This is likely due to the ability of the tumour to move laterally within the lung tissue. The small probe would presumably be less likely to cause the tumour to shift if it wasn't directly centred over the lesion. Likewise, the largest contact area would be more likely to overlap the entire tumour, again not resulting in a shift. Alternatively, when palpating with Probe D, with a curved face, or Probe A, which has a contact area close to the projected size of the tumour, the tumour may shift laterally if the advancing probe is not directly above it. Additionally, for the purposes of locating a tumour using kinesthetic feedback alone, a smaller probe diameter would enable the edge of the tumour to be localized with much better resolution.

In order to quantitatively validate that the physical properties of the simulated tumours approximated that of real tumours, indentation tests of both artificial and real tumours are being considered as part of a future study.

V. CONCLUSION

This paper has outlined experiments used to determine the kinesthetic feedback performance necessary to locate tumours in lung tissue by discerning differences between the force reflected when palpating the tumour and the surrounding healthy tissue. The results indicate that comparing peak palpation force reveals the most marked difference in the presence of the tumour and suggest a required sensing range and resolution of 0–10 N and 0.01 N, respectively. The results also indicate that a probe tip with a flat face performed better than a curved face. Probes with a face area that is larger than the anticipated tumour, or much smaller, performed equally well.

This information is potentially useful in the ongoing development of kinesthetic sensing methods for robotic or handheld tumour localization applications that attempt to overcome the constraints of MIS. The results may also be applicable to tactile sensing methods for localizing lung tumours.

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