

Using The BioTac as a Tumor Localization Tool

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ABSTRACT

Robotically-Assisted Minimally Invasive Surgery (RMIS) offers many benefits to patients, yet introduces new challenges to surgeons due to the loss of tactile feedback that would be available in open surgery. This makes many intraoperative procedures such as tumor localization or other technically intricate and delicate tasks increasingly difficult. Reestablishing the ability to feel for surgeons during RMIS would improve the quality and safety of these surgeries and facilitate conversion of many procedures requiring touch that are traditionally performed as open-surgery. In this research a biomimetic tactile sensor (BioTac, SynTouch LLC) was evaluated for localization of artificial tumors. Various signal processing techniques implementing spatial and temporal derivatives were implemented into a graphical user interface to aid in the localization of tumors when explored by a human operator. The ability to localize tumors using the BioTac sensor was compared to performance of the human finger. The BioTac sensor was found to be particularly effective for superficial tumors (3mm deep), achieving a detection rate of 94.1%. The BioTac was also able to detect small tumors 3mm in diameter at a detection rate of 61.5%, and tumors at a depth of 12mm with a detection rate of 60.0%. While human subjects were more effective at localizing most tumors, the BioTac was often able to do so at lighter forces.

Keywords: Tactile sensing, tumor palpation, minimally invasive surgery

Index Terms: Haptic devices, Remote Medicine, User studies

1 INTRODUCTION

Minimally invasive surgery, or laparoscopic surgery, is an alternative to open surgery permitting a surgeon to operate on a patient with laparoscopic tools through small incisions made in the abdomen. Robotically-Assisted Minimally Invasive Surgery (RMIS) is an enhancement to this, taking advantage of robotic control algorithms to simplify the process and make control of movements more intuitive to the surgeon. The benefits of RMIS to the patient are numerous, including reduced trauma and shorter recovery times [1]. However, these procedures eliminate tactile feedback that surgeons traditionally have available during open surgery. Tactile feedback is especially important when surgeons palpate tissue. Because of this, many operations that could benefit from RMIS are still conducted in open surgery because the intraoperative localization of internal structures is difficult in

RMIS [2]. In laparoscopic surgery, surgeons have been known to insert fingers into access ports for tactile feedback [3]. In RMIS, where such probing is more difficult, it is common for surgeons to rely on preoperative scans or a simultaneous endoscopy to localize tumors but this is time consuming and expensive. Furthermore, it is proposed that tactile feedback can make RMIS more intuitive, decreasing the length of these procedures, which in turn would reduce both financial cost and anaesthetic morbidity. The economic argument for RMIS hinges on reduced overall morbidity and shorter hospital stays to offset the added costs of the operation itself [4]. Restoring touch to surgeons should decrease both operating time and post-operative morbidity, reduce the incidence of reexploration surgeries, and extend the benefits of RMIS to a wider range of procedures.

A variety of tactile sensor designs have been investigated for use in RMIS. The most common design implements pressure-sensitive arrays that analyze localized pressure increases on a relatively hard surface to identify a lesion [2]. A simple, compact and inexpensive four-element one-dimensional array tactile sensor was developed by Dargahi, but the one-dimensional sensor configuration requires many movements to build a pressure map of the tissue [5]. Another tactile imaging device based on piezoresistive sensors with a resolution of 1.5mm was created that builds contour maps of the stiffness of the surface of a region to detect tumorous lumps in the breast [6]. A similar 8x8 array of piezoresistive sensors was proposed by Kattavenos for the examination of the bowel for tumors, however the resulting prototype was too large for RMIS constraints [7]. A modified laparoscopic grasper with an array of 32 conductive polymer sensors was created at the Institute of Healthcare Industries in Germany [8]. The sensor's output is displayed in a color-coded map of the tissue. A limitation with the system's mechanical design is that not all the tissues are graspable.

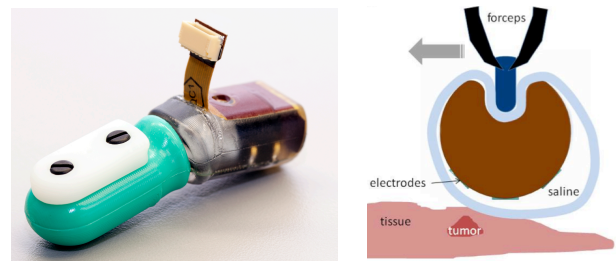


Figure 1: The BioTac (left) utilizes electrodes surrounded by a conductive liquid to measure normal and shear forces. As the BioTac slides over a surface, its elastomeric skin and the underlying liquid layer are deformed, changing the electrical resistance measured by the electrodes (right).

Most tactile sensors that have been explored measure normal forces and are insensitive to shear forces; however, the side-to-side palpation methods a doctor uses suggest that shear forces may play an important part in tumor localization. Common palpation techniques include circular motions and sliding along

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tissue. The BioTac (Figure 1) is a novel tactile sensor that has compliant mechanical properties similar to a human finger and is capable of similar shear force sensing. Additionally, the elastic covering of a rigid core containing sensory electrodes is very suitable for sterilization procedures that would be required in practical applications. In these studies the potential of the finger-sized BioTac to localize tumors is investigated. In the future, the design will be miniaturized for compliance with smaller laparoscopic ports.

2 METHODS

2.1 The BioTac

The BioTac (Figure 1) emulates the finger's sensing properties by measuring skin deformation [9], [10], vibrations [11], and temperature [12]. This research utilized skin deformation, which is sensed as changes in the impedances of electrodes on the surface of a rigid core and in contact with a layer of saline injected under the silicone elastomeric skin. It has been proposed that a normal-force sensitive probe requires a sensing range on the order of 0–10N and a resolution of 0.01N to localize tumors via palpation [13]. While the BioTac possesses this sensitivity using fluid pressure [11], it cannot localize such small forces until about 30mN of force [14]. The force sensing range of the BioTac using the impedance sensing modality is 30mN to 50N.

2.2 Tumor Fabrication

A set of artificial tumors of different sizes, depths, and hardness were created in substrates of varying hardness. For this research, all combinations of the following parameters (except when substrate durometer was equal to tumor durometer) were used:

- Substrate Durometer: 10A and 30A
- Tumor Durometer: 30A, 40A and 60A
- Tumor Diameter: 3.18mm, 6.35mm, 12.70mm and 25.4mm
- Tumor Depth: 3mm, 6mm and 12mm

All durometers are measured in Shore durometer type A. Tumor models were molded from urethane rubber with a surrounding silicone “tissue” layer. Other tumor fabrication approaches include silicone tumors surrounded by a water-gelatin mixture or injecting a water-agar mixture into an ex-vivo tissue [13]. The substrates in this study were chosen because they are similar to the elasticity of soft tissue, as observed by the second to last author (G.E.L.) who has medical training. The durometers of the tumors were chosen because the hardness of a tumor varies qualitatively from about the hardness of a rock to a grape [2], which fall within the ranges used. A Plexiglas mold was used to create hemispherical tumors of the various diameters. These tumors were then embedded into softer silicone at specified depths by layering silicone below and above the tumors. The tissue substrates were 13.5 cm long by 5.0 cm wide by 2.5 cm depth and were each embedded with three to four phantoms. A complete set of 60 tumors was created per the specifications above in addition to two controls at each substrate durometer with no tumors. Post-curing, the specimen was coated with a small amount of KY Jelly in order to improve the lubrication of the silicone and create an environment similar to what can be expected in a surgical environment.

2.3 Signal Processing

The BioTac was moved along each of the specimens by hand while electrode impedance values were recorded using a graphic user interface (GUI) available from SynTouch. The data were

analyzed in Matlab to identify useful signal processing techniques. Some of the more effective visualization techniques (as discussed below) were translated into a GUI in LabVIEW for real-time feedback to the operator.

2.3.1 Temporal Derivatives

In order to enhance the saliency of the tactile signals during palpation movements, the electrode impedances were differentiated with respect to time. After differentiation the electrode readings were put through a second order Butterworth low pass filter with a cutoff frequency of 5 Hz in order to reduce noise unrelated to the slower exploratory movements. The differentiated and filtered signal was squared to enhance the signal-to-noise ratio and increase the distinction between the substrate and the tumors.

2.3.2 Spatial Derivatives

To localize the tumor, spatial derivatives were used to find the location of the tumor with respect to the electrode array. To accomplish this, the difference between two adjacent electrodes in the same plane was taken. Referring to Figure 2, electrodes positioned horizontally in a row are in the same plane. The resulting graphs were then analyzed where there was a known tumor. The electrodes in the first (1, 4, 6) and last (11, 14, 16) rows and in the tip (7, 8, 9) were ignored because these points were not in contact under normal palpation. The spatial derivatives were additionally analyzed to determine whether it was possible to estimate the size of the tumor.

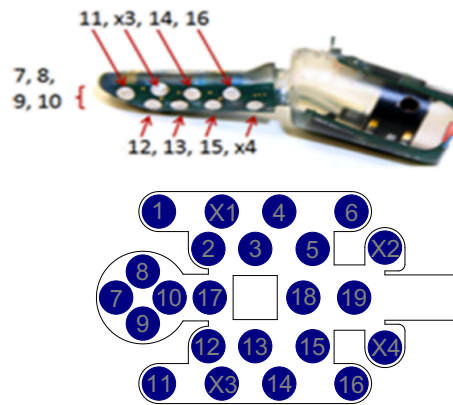


Figure 2: The BioTac electrode configuration. X's are reference electrodes; E impedances are measured with respect to the common reference electrodes.

2.4 Evaluation

Tumor detection using the BioTac was performed by the first author (M.S.A.), who had the most experience handling the BioTac and interpreting the GUI. Samples were prepared with a lubricant and placed by an assistant so they were visually occluded to the subject. The subject could freely move the BioTac and observe the GUI, but was not permitted to directly palpate the tissue. The time to localize the tumor after first contact was recorded by the assistant. A force plate (AMTI He6x6-16) measured the forces used during palpation to record the maximal force used to detect a tumor.

2.5 Comparison with Human Finger

In order to compare how the BioTac performs in contrast with a human finger, a blind study was conducted in which six subjects

without medical training, were asked to use their finger(s) to palpate a specimen and indicate whether the specimen had a tumor embedded within it. The subjects were made up of a combination of SynTouch employees and USC students. Prior to being blindfolded, the subjects were allowed sufficient time for training. Subjects were instructed to use whatever palpation methods they desired to accomplish the task. Each participant was timed in each trial and palpation forces were recorded using the force plate. Each subject was randomly presented with 30% of the samples, as going through the entire set was very time consuming and extremely tiring for the fingers and thumbs. The tumors were classified into sixteen groups of difficulty, and one tumor was randomly selected from each group to be tested on each subject.

3 RESULTS

The results from the signal processing techniques and a comparison of the tumor detection abilities of the human finger versus BioTac-facilitated sensing are described below. The averages shown for the human finger are averaged over each subject's average performance. Table 1 shows an overall comparison between the human finger and the BioTac as compared by force, time, and accuracy.

Average	Finger	BioTac
Accuracy	87.63 +/- 9.16%	72.48%
Force	38.76 +/- 16.70N	25.025 N
Time	14.16 +/- 3.39s	50.53 sec

Table 1. Summary of detection rate, force, and time for human finger versus BioTac. Error regions indicate standard deviations between subjects.

Depth	3 mm	Finger	BioTac
		87.5%	94.1%
6 mm	12 mm	87.2%	65.0%
		83.3%	60.0%
Size	25.4 mm	96.6%	93.3%
	12.7 mm	96.9%	71.4%
	6.35 mm	87.0%	60.0%
	3.72 mm	62.1%	61.5%
Hardness Difference	50A	83.3%	63.6%
	30A	91.5%	78.3%
	20A	72.7%	83.3%
	10A	90.0%	54.5%

Table 2. The results with the human and BioTac fingers are shown in comparison to changes in tumor features, averaged out over all other variables. Hardness difference is calculated as the difference in durometer between the substrate and tumor.

3.1 Temporal Derivatives

The signal processing performed on the raw electrode impedances improved the saliency of the signal for detecting tumors, as illustrated in Figure 3.

As shown in Figure 4, all tumors were detectable in the 10A hardness substrates except the smallest tumor (diameter 3.72mm) at 6 and 12mm depth. These tumors were, however, detected in the harder 30A substrate 30A. With the deeper tumors, it was helpful to move the BioTac over the tumor centred about electrode 17 (see electrode configuration in Figure 2), with an angle of about 30 degrees. It took multiple attempts to get a good orientation for the BioTac with respect to the specimen, after which clear signals were obtained.

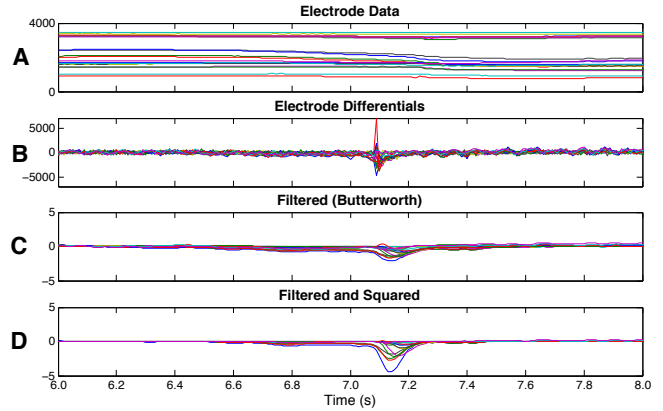


Figure 3: The BioTac was run along a 6.35mm diameter tumor of hardness 40A at a depth of 6mm embedded within silicone of hardness 10A. Graph A shows the raw electrode data. Graph B is the derivative with respect to time. C shows the derivative taken after a low pass filter was applied on the data. D is the square of the graph above it, taken to enhance signal-to-noise ratio. In D, the tumor is easily distinguishable from the surrounding tissue.

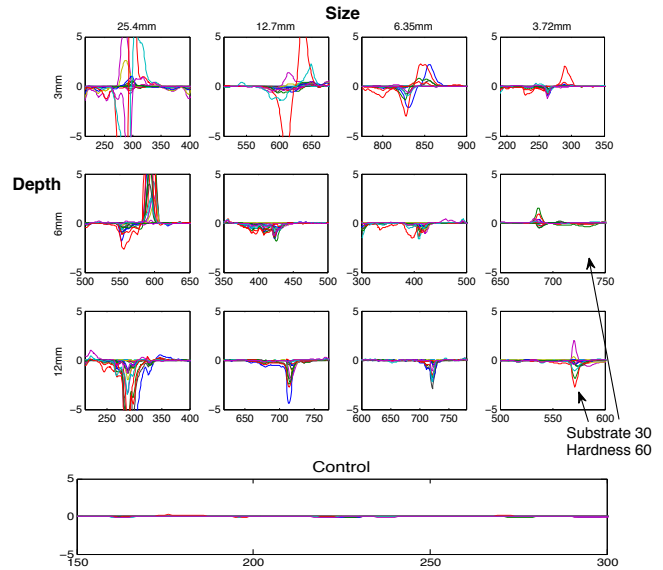


Figure 4: Substrate 10A, hardness 30A tumors are shown. From left to right, the size of the tumors decreases, and from top to bottom the depth of the tumor increases. The tumors are easily distinguished from the surrounding tissue and are characterized by a spike in the derivatives. Noise is minimal as can be seen by the control (bottom). Substrate 30A, hardness 60A tumors are shown for the 3.72mm diameter at depths 6mm and 12mm because these were not detectable in the substrate 10A.

3.2 Spatial Derivatives

The BioTac electrode configuration provided only a limited set of spatial derivatives that did not provide enough information to characterize the size of tumors; however, as shown in Figures 5, the results show promise in localizing tumors on the surface of the BioTac.

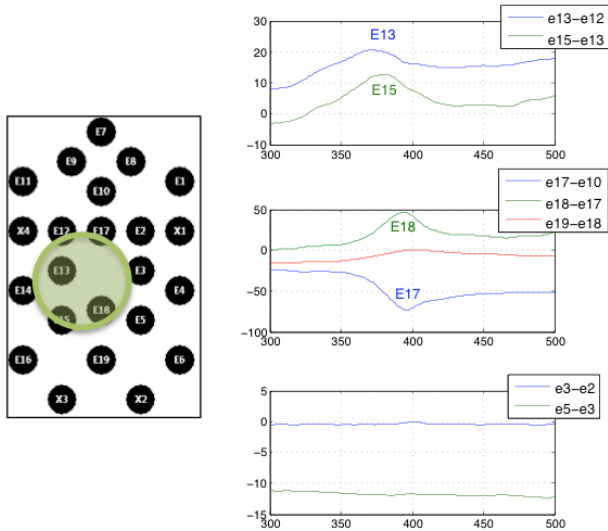


Figure 5: The spatial differential for a tumor with diameter 25.4mm, depth 6mm, hardness 40A embedded in substrate 10A. The inset left indicates the location of the tumor, and the graphs display the spatial derivatives for each plane of electrodes. This indicates that the BioTac ran over the tumor at electrodes 13, 15, 17, and 18.

The spatial derivatives were displayed in a color-coded GUI, which improved saliency as shown in the supplemental video.

3.3 Human Study

Table 2 shows that the smaller tumors were much more difficult to localize than the larger tumors. Perhaps surprisingly, depth was not as important a factor as size in its effect on ability to localize the tumors. Testing larger depths might have made a larger effect on tumor detectability. Finally, hardness of the tumor had little to no correlation with the ability to detect the tumors. As shown in Figure 6, the human finger outperformed the BioTac by a small margin.

The BioTac's main difficulties were in false positives and speed. Because it takes multiple passes to detect tumors, it took longer to localize tumors with the BioTac than simply receiving direct tactile feedback. However, this is reasonable, as teleoperation would be expected to be slower than direct manipulation. Using the BioTac, tumors were falsely detected when there were none in almost all trials. When the BioTac is stroked manually along the specimen, any imperfections in the surface or changes in velocity or normal pressure can cause changes in electrode impedances that look similar to a tumor. It should be noted that the tumor models had imperfections caused by the initial studies with the human fingers, which were conducted prior to the BioTac evaluation. The control models were particularly affected because participants used more force when they were unable to detect a tumor. Thus, the controls had many fingernail marks and divots, and these imperfections were picked up by the BioTac. In order to prevent false tumor detection where a "tumor" was actually a model imperfection, the experimenter compared actual tumor location with the result reported by the subject in both the BioTac and human portions of the study.

As shown in Figure 7, subjects who used more force were able to perform the best in successfully classifying tumors. Consistently lower forces were applied to the BioTac than

subjects applied with their fingers (on average, 65% less), yet the BioTac still had a classification accuracy that fit the trend of the other subjects. In the Time graph, the BioTac data point is far from the trend with the human finger.

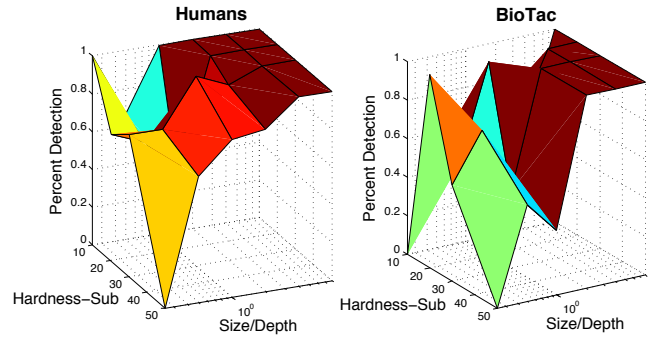


Figure 6: The human study results are shown with the percent detection of humans (right) in comparison with the BioTac (left), plotted against tumor types. For visualization purposes, the tumor factors were consolidated into two: the x-axis shows the difference in tumor and substrate hardness, and the y-axis shows the ratio of the size to depth.

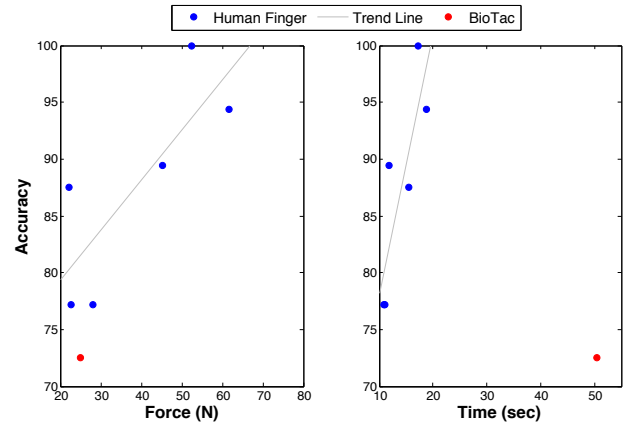


Figure 7: The above graphs show the average time and force taken by each subject (blue dots), mapped against their percent accuracy. A best-fit linear curve was drawn through the data to show the trend line. The red dot represents the percent accuracy for the BioTac.

4 DISCUSSION

In comparison with the human finger, the BioTac was slightly inferior. Using the BioTac, even the smallest surface tumors tested (3.72 mm diameter, 3mm depth) could be detected. Every tumor except the smallest diameter tumors was detected even at the largest depth (12mm). The temporal derivatives were an effective method of localizing the tumors. The spatial derivatives also yield useful information that can be used to find approximately where on the sensor the tumor was located. This is likely to work better with a longer array of closely spaced, coplanar electrodes. Other techniques such as normal forces can be used to further localize tumors after initial detection.

4.1 Temporal Derivatives

The manner in which the BioTac was moved along the specimen was most important for clear results. With more difficult tumors –

smaller and deeper – multiple passes and specific orientations were needed. As shown in Figure 6, the smallest tumor was detectable using the BioTac in the 30A durometer substrate, but not in the softer 10A durometer substrate, where the distinction between tissue and tumor hardness was larger. This result is somewhat surprising, but is probably due to the fact that the tumor could be displaced in the softer tissue by the forces of the exploratory movement. This difficulty is similar to tumor localization in the bowels, a very soft organ in which tumor detection is very difficult. A different palpation method is preferred for the bowel, and surgeons “run the bowel” in order to detect tumors bowel [16].

4.2 Spatial Derivatives

The spatial derivatives give more accurate readings with the harder, more superficial tumors. Redesigning the electrode layout could provide more data points and reduce the noise in the spatial derivatives. The spatial differentials were not sufficient to estimate the size of the tumors because larger tumors were not longer than the flat sensing region of the BioTac. The curve of the tumors prevented palpation along the entire circumference of the hemisphere, and thus the larger tumors exhibited similar signals.

4.3 Normal Forces

Another effective localization technique not discussed above is utilizing normal and tangential forces to orient the BioTac toward the tumor, as done in [10]. By equalizing opposite electrode impedances in the tip of the BioTac (electrodes 7 and 10, and 8 and 9), the normal and tangential forces could be balanced, reorienting the BioTac as necessary to preserve this balance. This strategy appeared to be effective for surface tumors when the tip of the sensor was near the edge of the tumor. This exploratory technique is time consuming and is only useful when the general location of the tumor is already known and a more accurate outline is desired.

4.4 Human Study

On average, the experimenter using the BioTac was capable of detecting 70% of the phantom tumors, while subjects using their own fingers were able to detect 85% of the tumors presented to them. The BioTac required significantly more time than the human finger, but also used less force. Lower force is optimal for reduced tissue damage. The surface of the BioTac is compliant, which puts lower stress concentrations on the surface it is probing, which is an added benefit for tissue palpation. Both in using the BioTac and the human finger, localizing small tumors was difficult. The BioTac additionally suffered from false positives. The specimens, particularly the controls, were damaged in the human portion of the study, which was conducted prior to the BioTac evaluation. Fingernail marks and divots appeared to cause many false positives. Lack of visual feedback meant that it was impossible for the controller to know whether the GUI showed a tumor or an imperfection in the specimen. In an actual surgical environment, the surgeon has visual feedback, which would aid in avoiding false positives from surface features. The BioTac performed very well on very small tumors.

On average, the BioTac was used with less force than the biological finger, but this may reflect the relatively high friction between the BioTac and the substrates despite lubrication. The friction between the BioTac and real biological tissues such as within the abdomen remains to be determined.

In future studies, it would be useful to compare the performance of surgeons' ability to detect tumors against the abilities of

surgeons to perform tumor localization using the BioTac, as surgeons have more expertise in tissue palpation.

5 CONCLUSION

This study explored ad hoc signal processing methods that were demonstrated to be useful to localizing tumors. It is perceived that additional palpation techniques including side to side palpations, and additional signal processing approaches such as those including shear forces are worth exploring. Further, because the BioTac was effective at localizing small tumors in signal processing, but not in the human study, this shows additional room for improvement. Nonetheless, the BioTac shows significant potential for use in RMIS. Its reduced accuracy in comparison to the human finger and increased detection time is offset by the fact that the sensor is intended for use in RMIS. In a blind study, using the BioTac, 72% of the tumors were detected, and these were detected with a lower average force than using the human finger. Ultimately, introducing a tactile sensor to RMIS operations will create improved surgical capabilities for the surgeon, and thus an improved experience for the patient.

In the future, the BioTac will be redesigned specifically for use in surgical environments. In redesigning the BioTac, all physical characteristics must comply with RMIS standards. The BioTac will be straight and smaller in diameter to fit through typical surgical ports. It will need to be sterilizable and easily assembled and filled with saline in the operating room. The skin thickness, inflation volume and electrode configuration will be optimized for RMIS applications. This should substantially improve sensitivity and spatial resolution (currently 2mm). The fingerprint pattern on the BioTac skin will be eliminated, which should reduce vibration noise and perhaps frictional forces during sliding, as well as simplifying manufacture. A single element ultrasound transducer may be integrated into the sensor in order to provide additional information about subsurface features.

The visual feedback method for displaying the BioTac's sensor data may not be ideal, particularly if it distracts the surgeon from the view of the surgical field. An alternative to this is tactile feedback such as the tri-axial force tactor being developed at the University of Siena, which can be worn in the fingertip, explained in detail in [15]. This tactor can produce normal and shear forces on the fingertip but does not provide spatial information. This kind of tactile feedback could be faster and more intuitive for the surgeon to understand, perhaps complementing rather than completely replacing visual feedback.

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