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Behavioral Characteristics of Manual Palpation to Localize Hard Nodules in Soft Tissues

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Abstract—Improving the effectiveness of artificial tactile sensors for soft tissue examination and tumor localization is a pressing need in robot-assisted minimally invasive surgery. Despite the availability of tactile probes, guidelines for optimal palpation behavior that best exploit soft tissue properties are not available as yet. Simulations on soft-tissue palpation show that particular stress-velocity patterns during tissue probing lead to constructive dynamic interactions between the probe and the tissue, enhancing the detection and localization of hard nodules. To the best knowledge of the authors, this is the first attempt to methodically evaluate the hypothesis that specific human palpation behaviors (defined by the fingers' velocity, trajectory and exerted force) directly influence the diagnosis of soft tissue organs. Here, we use simulation studies involving human participants to establish open hypotheses on the interaction and influence of relevant behavioral palpation variables, such as finger trajectory, its velocity, and force exerted by fingers on the accuracy of detecting embedded nodules. We validate this hypothesis through finite element analysis and the investigation of palpation strategies used by humans during straight unidirectional examination to detect hard nodules inside silicone phantoms and ex-vivo porcine organs. Thus, we conclude that the palpation strategy plays an important role during soft tissue examination. Our findings allow us, for the first time, to derive palpation behavior guidelines suitable for the design of controllers of palpation robots.

Index Terms— Minimally Invasive Surgery, Medical Robotics, Palpation, Tactile sensors

I. INTRODUCTION

THE realization of artificial tactile feedback is an important and desired feature for various surgical systems including surgical robots. It has already been established that the presence of tactile feedback would increase the effectiveness of Robot-assisted Minimally Invasive Surgery (RMIS) and lead to better clinical outcomes [1–3]. In order to implement tactile sensing for this type of procedure, researchers have

developed a range of sensing devices [4–6]. In particular, attention is paid to developing probing devices that can scan the surface of soft tissue and identify the presence and location of malignant or benign formations [7–9]. Traditional open surgery allows direct access to organs, and therefore the possibility to palpate an organ. Palpation during RMIS is considered desirable, but can be only achieved indirectly through an appropriately programmed robotic tool deployed via a small opening in the abdomen and equipped with tactile or force sensing capabilities. The development and practical implementation of tactile sensors for medical applications started at the end of the 20th century [3], [10]. However, palpation tools are not used in RMIS. The main reason for that is that only well tested and approved devices can be used for surgical applications. Likewise, the result of tactile examination, such as detection of abnormalities should be accurate and reliable. However, the implementation of robot-based organ palpation is complicated due to the nonlinear behavior of soft tissues as well as the uncertainties of the environment that are caused by internal liquids and displacement of internal organs. The variability of tactile information should be reduced to a minimum through optimal design of the probing devices and by choosing the most appropriate probing behaviors, given the medical context (such as specific organ or type of disease). This paper focuses on studying effective ways of soft tissue tactile examination; the detected strategies and behaviors allow the detection of lumps in organs with higher accuracy than approaches that do not employ strategies.

In-vivo and ex-vivo studies on human organs can be conducted to test our hypotheses [11], [12]. However, the location of a tumor can change due to the interaction forces. Thus, the effectiveness of the examination, especially with regards to tumor localization, can be complicated. Another approach is to use finite element simulations to understand the responses of soft tissue [13], [14]. However, such models are often very simplified and do not model all facets of real surgical conditions. Therefore, in order to understand the effectiveness of a soft tissue examination approach, we suggest studying how humans use their hands to palpate soft tissue. This paper studies various aspects of manual palpation, which once understood, have a high potential to improve the palpation-based robotic examination of soft tissue organs.

Manual palpation of soft tissue is a technique making use of tactile sensation – a method commonly applied to examine

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soft tissue during open surgery. The palpation movements and strategies are specific to the body area being examined. For instance, in prostate examination, a global organ palpation is carried out first; then an area of interest (e.g. near a found abnormality) is focused on and examination movements, such as tapping, vibration-inducing movements and sliding are applied locally [15]. It is reported in the literature that the method of physical examination of soft tissue is not standardized and may vary depending on the physician's preferences [16]. During one single examination, various techniques (such as circular movements and tissue rolling between finger) are applied [15], [17]. It is noted that the effectiveness of manual palpation to detect lumps and other abnormalities is constrained by the physical limits of human tactile perception and by physician's palpation abilities.

Existing palpation studies can be divided into two groups. The first set of works is concentrated on the comparison of the performance of human tactile sensation with existing tactile devices [18], [19]. In that case, the main focus is on the evaluation of sensitivity and accuracy of a particular tactile device. Other researchers discuss clinical studies describing methods of manual soft-tissue examination for different organs, such as patterns of movement and recommendations for manual palpation procedure [20], [21]. These studies evaluate the accuracy and tumor detection rates for manual palpation, but are not providing general physical quantifications for different movement types during palpation. A study [22] discusses the importance of force and velocity during virtual palpation simulation via a haptic device. Furthermore, this work highlights the dependence of the magnitude of the finger velocity during palpation with regards to the stiffness of the environment.

The objective of our study is to test several probing behavioral hypotheses to identify the most fruitful manual palpation strategies for the localization of tumors in soft tissue during straight unidirectional movements. Based on the relevant literature, we test two open hypotheses about the characteristics of manual palpation to understand applied strategies to detect and localize hard formations, such as nodules in soft tissue: 1) the palpation speed influences the correct localization of an embedded hard nodule; 2) the localization and detection rate of nodules can vary depending on the palpation force and velocity. To the best of our knowledge, this is the first paper that tests force-velocity modulation characteristics of manual palpation to detect hard nodules in soft tissues.

The rest of the paper is organized as follows. In Section II, methodology of experimental studies and validation studies on palpation are presented. Section III discusses finite element simulations (FE). Then, in Section IV the experimental studies and data analysis on manual palpation are described. Section V concludes the paper.

II. MANUAL PALPATION STUDIES

A. Evaluation of Manual Palpation

Previous clinical studies on manual soft-tissue examination

behaviors for different organs, [20], [21] suggest that patterns of movement of fingers do matter in the effectiveness of detecting hard nodules in soft tissue. However, there is no fundamental evidence supporting the argument that temporal modulation patterns of movement variables play a role during palpation. Validation palpation tests were carried out to understand the possible influence of variable palpation behavior on the process of the localization of hard nodules. This test is designed to analyze the strategies, evaluating velocities, trajectories, and palpation forces that humans apply to detect hard inclusions. The subjects were first asked to apply "unrestricted" palpation, i.e. to palpate a phantom tissue with one finger in an unprescribed and unconstrained way, with the aim of detecting embedded nodules. One finger palpation is used in order to be comparable with artificial palpation approaches involving a single probe during RMIS [8].

This work was approved by the King's College London Biomedical Sciences, Dentistry, Medicine and Natural & Mathematical Sciences Research Ethics Subcommittee. A total of twenty subjects participated in this experimental studies. In the study group, ten of the participants were certified experts in palpation techniques with at least five years surgical experience - senior residents and fellows were gynecologists accredited by the Royal College of Obstetricians and Gynecologists (London). While the remaining subjects were considered novices with regards to soft-tissue palpation. The stiffness ratio between soft and hard silicone was chosen in such a way to correspond to the commonly found stiffness ratio between healthy soft tissue material and tumors [23]. Therefore, for the creation of the phantom tissue, silicone gel RTV6166 (Techsil Limited, UK) with mixture ratio 4:6 and 900 mPa·s viscosity was employed. To simulate artificial tumors, transparent silicone nodules were embedded in the phantom tissue. Hard silicone rubber compound RTV615 (Techsil Limited, UK) with mixture ratio 10:1 was used to fabricate hard spherical nodules with 4000 mPa·s viscosity. The silicone phantom used for evaluation studies (130×85×30 mm³), Fig. 1, contained four nodules of different diameters – 15, 12, 9 and 6 mm, all embedded 9 mm from the surface.

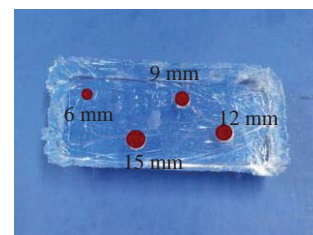


Fig. 1. Phantom tissue with the locations of embedded hard nodules used for evaluation palpation tests.

B. Experimental Setup

The experimental arrangement (Fig. 2) was designed to detect the finger pressure, trajectory and velocity, thus allowing the main characteristics of the finger movement to be recorded. The force values of the applied pressure were measured with a force/torque sensor (Mini 40, ATI industrial automation), which is a 6 degrees-of-freedom sensor with a force sensing range of ± 10 N in X and Y direction, ± 30 N in Z

direction and ± 0.5 Nm for torque readings; normal force resolution is 0.01 N. The sensor is mounted under a base plate, supporting the examined target material (i.e. the silicone phantom or the animal organ). To reduce the effect of friction the surface of the sample tissue is lubricated with gel substance that is typically used for ultrasound scans.

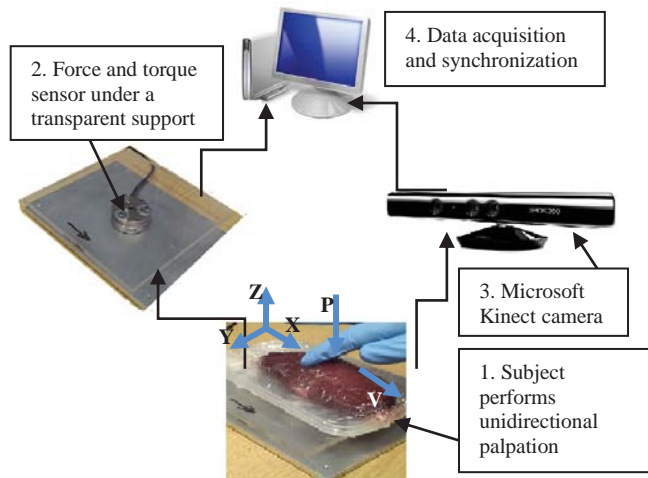


Fig. 2. Schematic arrangement of an experimental setup: the subject performs palpation with one finger (1) – the main palpation features are: applied pressure P , velocity V and trajectory in three-dimensional space XYZ ; the applied force is measured using a force/torque sensor, mounted under the transparent support plate (2) and the trajectory is measured by a three-dimensional vision system (3). All acquired sensor data is synchronized and processed (4).

A three-dimensional vision system (Microsoft Kinect camera system) was used to record the trajectories of the finger during the palpation tests. The Kinect system is equipped with a depth sensor and a video camera (640 \times 480 pixel resolution, image acquisition 30 fps). The OpenCV package for Microsoft Visual C++ was used to track the three-dimensional movements of a subject's hand while performing palpation. Spatial position readings were recorded and used to obtain the magnitude of the finger tangential velocity. Evaluation tests were carried out to check the measurement accuracy of the camera. The value of position accuracy depends on the velocity of the moving object, i.e., here, the finger. Therefore, to test the accuracy of Kinect system, the mean velocity of palpation was applied. Firstly, the hand position was recorded with the Kinect-based system, using a hand-tracking algorithm. Concurrently, the trajectory of the hand was recorded using stereovision (two separate cameras), and the position was obtained from a colored marker on the finger using the MATLAB Computer Vision Toolbox. The two-dimensional position values of the marker on the moving finger were analyzed from each camera separately; then the three-dimensional position of the marker in space was reconstructed. Comparing the obtained three-dimensional values from Kinect sensor and our stereovision system, we find the position accuracy for the Kinect camera to be 1-2 mm.

C. Data Analysis

Data processing and statistical analysis were conducted

using MATLAB 7.12.0 and R statistics i386 2.15.2 software packages. In order to smooth noisy peaks from the positional data, a second order low pass filter was used with cut-off frequency of 0.2 Hz and stop-band attenuation of 16 Hz. Three-way analysis of variance (ANOVA) and two-way t-tests were used in order to analyze the interaction between various palpation factors and conditions on the detection rate of hard nodules and to observe the sources of variations, where appropriate. The impact of a factor was considered significant, if the null hypothesis was rejected with a 95% confidence level, for $p < 0.05$. A Kolmogorov-Smirnov test was used to check if the data follows normal distribution.

D. Results of Validation Studies

As part of our analysis, we are interested in establishing whether there is a correlation between the palpation variables during hard nodule localization, based on results from validation palpation studies. To understand the mechanisms and behaviors used by subjects to obtain explicit information about the properties of the embedded nodule, we examined the experiments on “unrestricted” one-finger palpation. Fig. 3 demonstrates the distribution of palpation velocity and applied finger pressure over the phantom organ. Naturally, palpation parameters are variable and are based on the judgement of the subject. However, one can notice dependencies between applied force and velocity, as well as a certain type of behavior applied to the tissue at locations above the nodules. However, it is not possible to draw any conclusions about the impact of palpation force and velocity, based just on the representation of the parameters' magnitudes.

To observe the cross-modulations of applied pressure and velocity, we decided to investigate the local extrema of each measurement (force and velocity) and the associated concurrent values of the other measurement (velocity and force). Local extrema in this case are considered local maxima and local minima of force or velocity magnitude, and are found using a second derivative test. Fig. 4 shows the distribution of force and velocity for the local maxima and minima of the other measurement. The presented data are separately normalized with regards to the maximum value of each variable. The general trend is for velocities to increase in response to higher forces being applied. The velocity magnitude (Fig. 4a) does not vary significantly for maximum and minimum force. In addition, according to the two-way t-test there is no significant difference between the velocity at local minima and that for local maxima of force pressure ($p > 0.07$). However, the force values, corresponding to extrema values of velocity (Fig. 4b) belong to two different distributions ($p < 0.05$). The force magnitude tends to decrease for higher velocities, but showing a large deviation. These observations demonstrate that to explore a soft environment and to locate some hard inclusions in an efficient way one applies variable examination behaviors. However, to understand the characteristics of manual palpation one needs to examine the modulations of force and velocity in the vicinity of a buried nodule. For this purpose, FE simulations were carried out using force and velocity parameters, obtained

during evaluation palpation studies, followed by additional palpation experiments that are focused on unidirectional manual palpation.

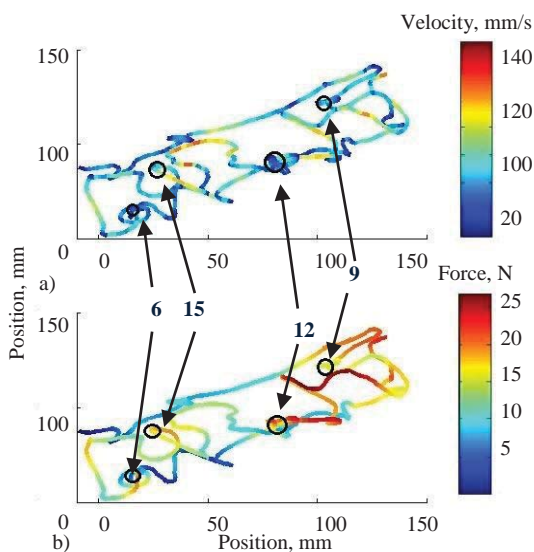


Fig. 3 Representative example of palpation path over a phantom tissue with four embedded nodules (diameters in mm marked with arrows): a) modulation of velocity magnitude, b) modulation of applied finger pressure.

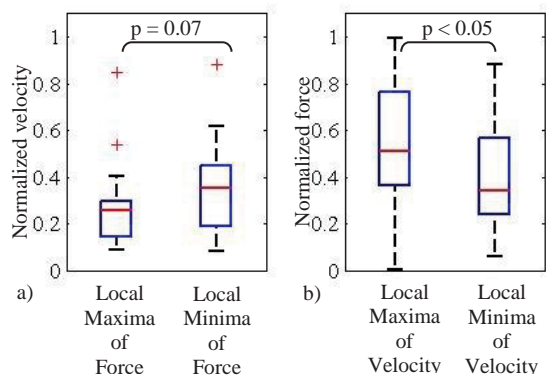


Fig. 4 Distributions of a) normalised force magnitude and b) normalised force magnitude; the y-axis shows the local minima (1) and local maxima (2) peaks of force and velocity measurements, respectively.

III. FINITE ELEMENT SIMULATIONS

A. Design of Finite Element (FE) Simulations

As first step to study the patterns of unidirectional manual palpation, FE analysis is carried out. Simulations can help to understand stress responses experienced by the soft tissue during tactile examination [24]. An important feature of manual palpation – the detection rate of hard nodules – depends on the magnitude of stress in the contact area with a finger. The higher the force per unit area is applied; the more stress is induced in that area. The analysis presented in this section will be used to explain the behavioral patterns of manual palpation.

The process of unidirectional one-finger manual palpation over a silicone phantom was simulated in an FE modeling environment. Validation experiments on manual palpation are used to obtain the input parameters, such as the velocity and

force exerted by the finger. To understand the impact of palpation behavior, these parameters were varied during our simulation study.

FE simulations were conducted in ABAQUS 6.10. The silicone phantom was modeled based on the studies described in [25] – a non-linear, isotropic, incompressible, and hyperelastic Arruda–Boyce model was used. The silicone phantom was modeled as a rectangular cuboid with dimensions $50 \times 50 \times 30 \text{ mm}^3$. The element size of the mesh of the FE model was 1 mm, using a quadrilateral element type. The diameter of the embedded spherical nodule was set to 10 mm and depth 2 mm, according to the experimental studies presented in Section IV (A). The fingertip contact was modeled as a discretely rigid (undeformable) sphere with 20 mm diameter. Based on validation simulations, it was found that the rigid sphere can be modeled with 20 mm diameter. The contact between the soft tissue and the indenting body was modeled as frictionless, assuming a perfectly lubricated surface. At the beginning of all simulations, the soft tissue was indented by 3 mm, according to the initial indentation used by subjects during palpation experiments.

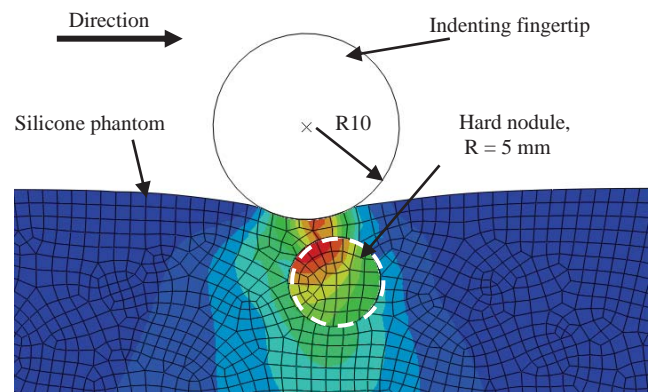


Fig. 5. FE simulation of stress in the silicone phantom indented with a fingertip (diameter 20 mm) above the nodule location (diameter 10 mm) for the location above the nodule. Here, the tangential velocity and the normal force are decreasing during the palpation movement.

B. Results of FE Simulations

To understand the possible combination of force-velocity modulations during palpation, four types of palpation behaviors in the vicinity of a hard nodule were simulated: a) decreasing tangential velocity (from 100 mm/s to 50 mm/s) and decreasing the normal force (from 15 N to 8 N); b) increasing tangential velocity (from 50 mm/s to 100 mm/s) whilst decreasing normal force (from 15 N to 8 N); c) constant tangential velocity (75 mm/s) and decreasing normal force (from 15 N to 8 N); and d) no modulation in force (12 N) and velocity (75 mm/s) – both variables remain constant whilst moving across the nodule.

For demonstration purposes, Fig. 5 shows the FE simulations with the deformation at the contact point above the nodule; in the shown example, the tangential velocity decreases while the normal force is decreases.

The results of the simulations with hard nodule buried 2 mm from the surface are shown in Fig. 6. One can observe

that applied force-velocity modulations are causing different stress responses in the area around the hard nodule. The decrease of the stress magnitude can be observed after the nodule location has been reached. The responses from the simulations c) and d) show some peaks not only in the area of the nodule but also after it has been detected. However, these peaks are not observed for the strategies shown under a) and b). For the decreased velocity strategy (b) the stress distribution is relatively uniform and less intense. The result of simulation with increasing-velocity strategy (a) shows one high peak before the nodule, only.

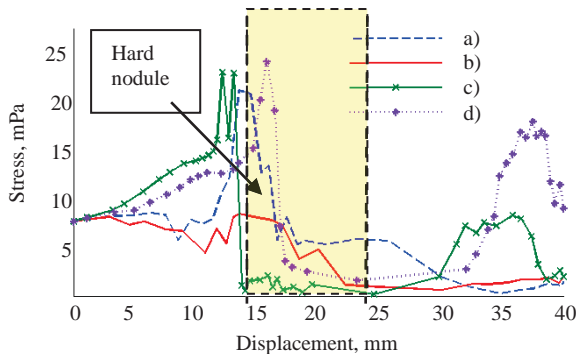


Fig. 6. FE simulation of stress for different palpation strategies: a) increased velocity and decreased force; b) decreased velocity and decreased force; c) constant velocity and decreased load; d) constant velocity and force.

Different palpation behavior strategies, described by finger velocity and applied force, result in different stress responses, with great potential to lead to different tactile experiences in humans. Therefore, taking into account the simulation results, it is required to test further the validity of the proposed hypotheses with the help of palpation studies.

IV. ASSESSMENT OF PALPATION TECHNIQUES

In order to test the hypotheses proposed in the introduction, two sets of palpation tests involving human participants and a test rig with silicone phantoms were carried out to understand the characteristics of manual palpation to localize hard nodules during unidirectional movement. In the first test, manual palpation strategies to detect hard embodiments within the silicone phantoms were studied. The impact of the velocity of subject's finger traversing over the tissue surface was recorded and examined during the second test. Two palpation tests are described hereafter:

A. Test 1: To Understand Strategies to Detect Hard Embodiments

1) Experimental Protocol

In order to further understand what kind of behavior is used particularly for nodule localization, the recordings of movements of the finger when positioned in the vicinity of the buried nodules are investigated. During this test, subjects were asked to palpate a silicone phantom block ($100 \times 100 \times 30 \text{ mm}^3$) in a linear unidirectional way in order to sense three hard inclusions, $9.4 \pm 0.8 \text{ mm}$ in diameter, along a pre-defined path (Fig. 7). According to TNM Classification of Malignant Tumors [26], the tumors in the T1 stage vary from 0.5 mm to

20 mm in size. This range of tumor sizes was modeled with a normal distribution of $9.75 \pm 1 \text{ mm}$. The distribution of the size of fabricated hard nodules was $9.4 \pm 0.8 \text{ mm}$, which was not significantly different from that of the corresponding tumor nodules ($p > 0.7$ according to one way t-test). Each subject performed five trials. Hard nodules were embedded 30 mm apart at different depths from the surface: 2 mm, 6 mm and 11 mm.

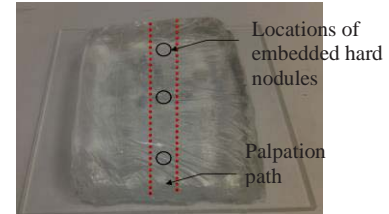


Fig. 7. Phantom sample used for unidirectional palpation with marked palpation path

During evaluation palpation tests, subjects were encouraged and allowed to apply any desired palpation trajectories and use various patterns, such as those learnt and developed during their professional practice. To measure the variability of applied force and velocity when the finger is in the vicinity of a hard nodule, subjects were asked to palpate the tissue in a unidirectional fashion. This type of palpation is one of the possible patterns for soft tissue examination. For instance, the work in [27] validates the autonomous exploration of the soft tissue with a snake robot employing a circular pattern. However, in this work we focus on a straight unidirectional palpation, as this pattern is the easiest for artificial palpation and enables fast and efficient coverage of the target area [28].

2) Results

There were three nodules placed along the palpation path for this test. Only the third nodule (buried 2 mm deep from the surface) was sensed by all subjects. As we are only interested to study the force and velocity modulations in the area of a detected hard nodule, the measurements from the region of the third nodule were analyzed separately. To observe the modulations of palpation behavior, the area around the nodule was separated into five interval regions. Fig. 8 demonstrates the location of the regions in respect to the location of the third nodule and displays the trajectory of the palpation path for one selected subject.

Each region represents a facet of the palpation movement in the vicinity of the nodule, Fig. 8. The area around the nodule is divided up into regions as follows: the region closest to the nodule has a width of 10 mm (Region 3), while regions further away from the nodule have a width of 5 mm (1, 2, 4, and 5). An experimental evaluation of the variables, force and velocity, for each region shows that the variance of each variable does not exceed 5%. The chosen unidirectional palpation path allows arranging the regions sequentially, and forcing the subjects to conduct the experiment along a straight line. However, the experimental study does not explore circular pattern based palpation, which would be more appropriate if the trajectory was following a curve or any other non-straight trajectory around a nodule, as it is often the case in the medical environment.

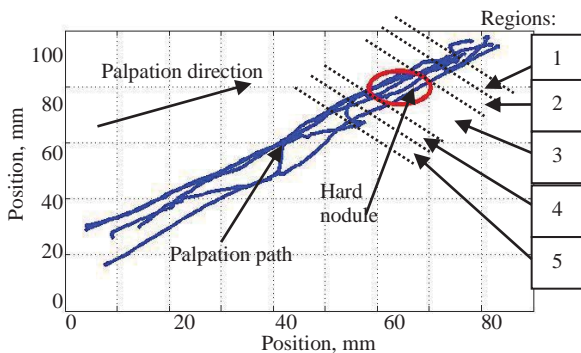


Fig. 8. The trajectory of palpation path – several trials of one selected subject; area of interest around the third nodule is shown with five interval regions (1-5).

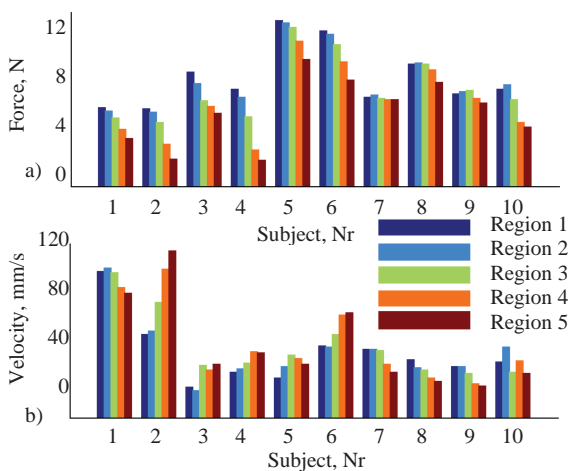


Fig. 9. Force (a) and velocity (b) distribution trends across ten selected subjects: subjects 1 to 5 are experts, and subjects 6 to 10 are novices.

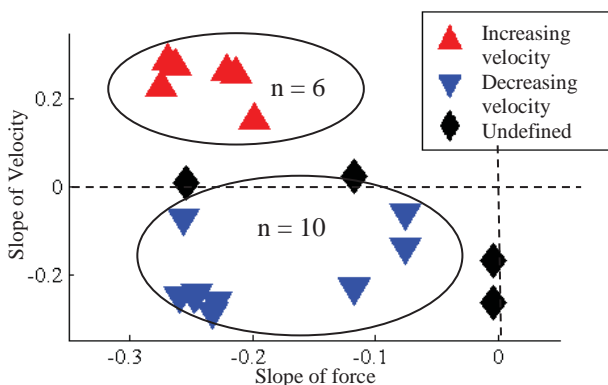


Fig. 10. Slope of force versus slope of velocity for subjects: two distinctive strategies can be identified – increasing and decreasing velocity. Outlier results are classified as “undefined strategy”.

Fig. 9 shows the mean force and velocity for each region applied by ten selected subjects – five experts and five novices. To identify possible trends in force and velocity modulation, the effects of force and velocity magnitude on the particular location (region) in the area around the nodule, and the influence of each individual subject were tested with the help of three-way ANOVA tests. The velocity computed based on the smoothed position profile was compared with the

optimal estimate of the velocity using a Kalman filter to obtain the average velocity error in each region. The average velocity error was found to be 0.11 ± 0.79 mm/s. The result showed that the pressure applied by the finger ($F_{(3,94)} = 7.92$, $p < 0.00001$) depends on the distance between the finger tip and the location of the hard inclusion. The effect of velocity and the impact from each individual was not significant ($F_{(3,94)} = 0.37$, $p = 0.55$ for force measurements and $F_{(3,94)} = 0.02$, $p = 0.9$ for the influence of each subject). These results show that the modulation of finger pressure is consistent for all trials, when the finger is in the vicinity of a detected nodule. However, the insignificance of the velocity magnitude in this context may suggest that the modulation of velocity changes differently among individuals due to some difference in their palpation behaviour. Alternatively, the modulation of velocity may not heavily contribute to sense a nodule.

To check the presence of different behaviors of palpation, a first-degree polynomial was fitted to the normalized mean values of force and velocity for each region (1 – 5), and the slope (gradient) of the polynomial fit of the force was plotted versus the slope of the corresponding velocity polynomial, Fig. 10. Two distinctive strategies were observed. It appears that 50 % of subjects have decreased both finger pressure and velocity while conducting an examination in the vicinity of the nodule. 30% of subjects have increased the velocity magnitude while at the same time decreased the applied force. 20% of the subjects do not vary velocity and force significantly. The group of experts participated in the studies performed on the same level as other subjects, i.e. showing similar behaviors like all other subjects.

To validate the statistical significance separately for behaviors with different variation of velocity, a three-way ANOVA test was conducted again for two separate strategies, i.e. increasing velocity with decreasing force and decreasing velocity with decreasing force. The impact of both finger velocity ($F_{(4,00)} = 9.16$, $p < 0.0001$) and finger force ($F_{(4,0)} = 4.83$, $p < 0.01$) in the vicinity of a nodule were significant for the strategy with decreasing velocity. Similar observations can be made for the strategy, where the velocity increases: the impact of both velocity and force are significant for locations near the nodule ($F_{(4,17)} = 4.59$, $p < 0.01$) and ($F_{(4,17)} = 4.36$, $p < 0.01$). Thus, one can see that during a soft tissue examination and hard nodule probing, the finger palpation properties can be varied in two different ways. In particular, the subject either increases or decreases the finger velocity while, at the same time, reducing the applied pressure. In addition, the smallest group of subject does not apply any force-velocity modulation.

B. Test 2: To Understand the Impact of Traversing Velocity

1) Experimental Protocol

This set of experimental studies was designed to evaluate the impact of the velocity of the subject’s finger during palpation on the detection rate of hard nodules. To perform manual palpation of an organ sample as close as possible to real organ palpation, subjects were asked first to localize embedded nodules during three sets of experiments, applying

unidirectional palpation across the surface of a semi-spherical silicone phantom, that was fabricated according to the size of an average human kidney (length 120 mm, width 65 mm, depth 30 mm). This was followed by three sets of experiments where unidirectional palpation was applied to an ex-vivo porcine kidney of average length 125 mm, width 80 mm and depth 30 mm. Hard nodules of 9.4 ± 0.8 mm in diameter were embedded at different depths from the surface – 1 mm, 3 mm and 5 mm (Fig. 11), in a such way that it is possible to detect the presence of a nodule for an average subject. The nodules in the tissue sample were inserted through skew cut from the posterior part, and the depth was assessed using a needle test rod. The principal difference of each experimental set was the applied palpation velocity – slow, natural and fast. “Natural” palpation velocity is defined as the speed of palpation that feels most comfortable to the subject. Consequently, slow and fast traversing velocities were defined as velocities that are lower and higher than the natural velocity, respectively. The range of the velocity magnitude is different for each subject, and is discerned during an analysis. One of the aims of this study was to evaluate how the velocity range varies across trials and across subjects.

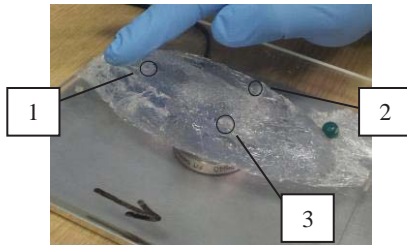


Fig. 11. Silicone phantom sample for Test 2, embedded nodules are marked (1, 2, 3).

2) Results

In order to get a better understanding of the impact of the finger velocity on the detection of hard nodules, additional studies were carried out. Fig. 12 shows the summarized data for Test 2 that presents the influence of separate factors such as subject, palpation medium, and traversing velocity, with regards to the detection rate of hard nodules. A three-way ANOVA test was carried out, to evaluate the importance of each separate palpation behavioral element and their influence on the detection rate. To compensate the individual bias, a weighting was applied on the detection rate of hard nodules for all sets of experiments for all subjects. The weight was calculated from the best performance of each subject with no false positives. We found that the type of palpation medium had a significant effect on the results ($F_{(3,99)} = 6.23$, $p < 0.0001$). While on the other hand, the subject ($F_{(3,99)} = 2.27$, $p = 0.14$) and the palpation velocity ($F_{(3,99)} = 0.61$, $p = 0.44$) did not influence the detection rate of hard nodules. Therefore, it is important to emphasize the significance of the correctly chosen palpation technique for a given environment and to analyze the process of soft tissue examination considering features of the target material.

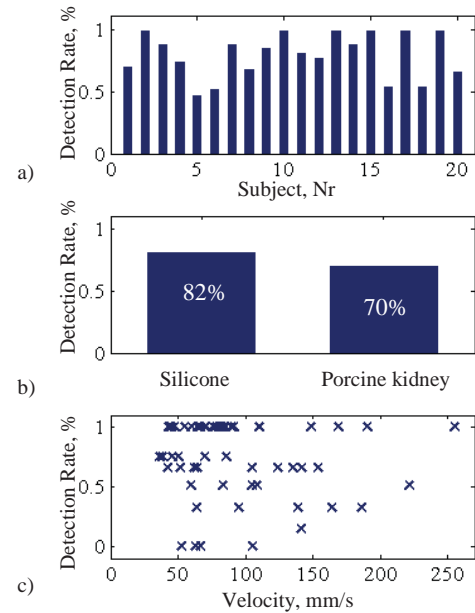


Fig. 12 Summary of hard nodule detection rate for a) different subjects (novices: 1-10, and experts: 10-20), b) silicone and porcine kidney, c) velocity.

To evaluate the impact of the traversing velocity for the given medium (here: the silicone phantom) a three-way ANOVA test was performed on the set of palpation cases. Firstly, we studied the group of subjects with low level of palpation experience. Three factors influencing the detection rate were considered – subject sequence number, applied pressure and the magnitude of palpation velocity. The velocity had a significant effect on the detection rate ($F_{(4,17)} = 3.14$, $p < 0.001$). While, the effects of both force and subject sequence number have shown virtually noeffect - ($F_{(4,17)} = 0.61$, $p > 0.3$) and ($F_{(4,17)} = 1.01$, $p > 0.4$), respectively. Secondly, the same analysis was carried out for the group of experts. Similarly, the impact of velocity was significant ($F_{(4,24)} = 8.97$, $p < 0.00001$). In addition, experts have used variable finger pressure to detect hard nodules ($F_{(4,24)} = 16.67$, $p < 0.00001$). This result confirms the importance of correctly choosing the traversing velocity and applied force; as is clear from the results, the experts achieved a higher detection rate.

To understand how the magnitude of velocity influences the detection rate of hard nodules, an analysis of different velocity magnitudes is carried out. Test 2 required to perform three trials using fast, natural and slow palpation velocities. The magnitudes of velocity were defined by the participants, based on their personal preference. Therefore, the values of the chosen palpation velocities for different subjects for the same trial (for instance, for natural velocity) are not the same. Thus, velocity data, which was defined experimentally, was divided into three groups based on their magnitude. For this purpose, k-means clustering was used. The data for experts and novices were processed separately. The results of the velocity distribution of both participant groups for three clusters are presented in Fig. 13. Compared with the experimentally defined velocities, there was 100%, 50%, and 61% correlation

for the group of novices and 75%, 38%, and 55% correlation for the group of experts with sets of fast, natural and slow magnitudes of velocities.

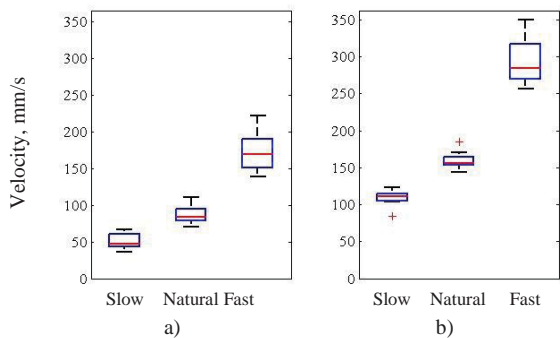


Fig. 13 Clusters of velocity distribution for a) novices and b) experts.

TABLE I
THE IMPACT OF PALPATION VELOCITY

Cluster	Experience	Detection Rate %	Velocity Magnitude mm/s
Slow	Novice	87	36 - 67
Natural	Novice	83	70 - 110
Fast	Novice	69	139 - 222
Slow	Expert	96	85 - 123
Natural	Expert	82	144 - 220
Fast	Expert	53	256 - 350

To evaluate the impact of the velocity magnitude, the detection rate for each cluster for each group was calculated as shown in Table I. It can be observed that the velocity magnitude applied by the group of experts is higher. However, the results for the detection rate for each set of velocity are similar. These results demonstrate the importance of the correctly chosen velocity magnitude. According to the data, the highest detection rate of nodules for the silicone phantom is observed for slow palpation velocity.

V. CONCLUSIONS AND DISCUSSION

In this work we test two hypotheses to understand the characteristics of manual palpation to localize hard nodules in soft tissues: 1) the speed of palpation influences the detection rate of hard nodules; and 2) force - velocity modulations during manual palpation influences the localization and detection rate of hard nodules. Thus, to get a better understanding of how the process of tactile probing during robotic surgery should be implemented, the manual palpation has been studied.

The presented work explores, with the help of the experimental studies and statistical evaluation, the influence of the palpation velocity on the detection rate of hard nodules. It was shown that the application of the appropriate palpation velocity increases the performance. The results of Test 2 show that experts use both applied force and velocity to locate hard nodules, while for novices just the variability of velocity significantly influences the detection rate. However, the detection rate for novices and experts does not differ

significantly. Our analysis has shown that experts use a complex modulation strategy, of both force and velocity. However, the novices take simpler approach that involves just velocity modulations as shown in Fig. 13 – the impact of exerted force is insignificant on the detection rate according to the statistical evaluation. Therefore, the first hypothesis holds more validity for the subjects with no palpation experience.

In this work we try to understand the main characteristics of manual palpation to detect hard nodules, with the help of palpation studies involving human participants. The developed experimental equipment allowed recording forces applied by subjects during palpation, as well as to follow the dynamics of the movement. By conducting tests on manual palpation, together with FE simulations, the strategies used to detect hard nodules during unidirectional palpation are examined. Based on the experimental evidence, we conclude that certain manual palpation strategies are applied to detect hard formations in soft tissue. Consequently, force - velocity modulations are applied differently for the detected palpation strategies. The correct combination of palpation variables for a given examination environment may lead to a higher detection rate of nodules. This supports our second hypothesis outlined in this paper.

Ten out of twenty participants in our studies had at least five years experience in manual palpation. Therefore, we expected their palpation trajectory to follow distinct patterns different from those of the non-experts. For instance, during the evaluation test, the majority of subjects have indicated that in order to locate a hard nodule and understand its shape, they have applied circular movements around suspicious area. Such types of palpation (we can call them high level techniques) are very useful to be applied during manual soft tissue examination, as they are easier to implement. However, the objective of this study is to provide a basis to design optimal robotic behaviors during soft tissue examination to localize hard nodules. Thus, we examine low level aspects of manual palpation, such as finger exerted pressure and palpation velocity.

To sum up, the detection and localization of stiff abnormalities, such as nodules, in soft tissues is influenced not only by the parameters of the probe, but also by the employed palpation strategy – the correct choice of force and velocity components for the given environment. The interaction dynamics of the finger or a probe during palpation is the result of the applied force-velocity modulations on the given properties of soft tissue. The work presented in this paper opens a question to develop behavioral guidelines for soft tissue examination during RMIS.

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