Salient Features of Soft Tissue Examination Velocity during Manual Palpation

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J. Konstantinova[1], K. Althoefer[1], P. Dasgupta[2], T. Nanayakkara[1]

[1]*Centre for Robotics Research, King's College London*

[2]*MRC Centre for Transplantation, DTIMB and NIHR BRC, King's College London*
jelizaveta.zirjakova@kcl.ac.uk

INTRODUCTION

The direct access to organs during Robot-assisted Minimally Invasive Surgery (RMIS) is limited and palpation is difficult to be implemented. Therefore, there is a need for the development of advanced tactile instruments to be used for intra-operative soft tissue examination and accurate localization of abnormalities, such as tumours.

Despite the availability of tactile devices for soft tissue examination [1], [2], the influence of probing behaviour on abnormality detection has not been studied yet. Our work underlines the importance of optimally chosen speed and load during tactile examination of the simulated viscoelastic environment [3]. In this work, we study the impact of velocity during manual palpation on the detection of hard inclusions in a silicone phantom and ex-vivo porcine kidney samples. In addition, validation results based on Finite Element (FE) simulations are presented. We present the evaluation of palpation velocity and show that it is a valuable source of information for the development of probing strategies and the design of new tactile sensing devices.

MATERIALS AND METHODS

Ten participants have been recruited to study the effects of velocity during manual palpation. All subjects had at least five years of surgical experience. Participants were asked to detect hard formations during three sets of unidirectional palpation tests using a silicone phantom and a porcine kidney sample. Three types of palpation velocities were employed during each test – slow, natural and fast. Natural velocity is defined as the palpation speed, which comes most naturally to participant.

To fabricate the soft phantom, silicone gel RTV6166 with a ratio of 4:6 and viscosity of 900 mPa·s was used. Three hard nodules, diameter of 10 mm, were embedded at different depths (3 mm, 5 mm) from the surface of the silicone material. To create the nodules, hard silicone compound RTV615 with a ratio of 10:1 and 4000 mPa·s viscosity was used.

The experimental setup, schematically shown in Fig.1, was used to measure the exerted finger pressures and palpation trajectories - the latter were used to calculate the associated palpation velocities. The applied forces were recorded with six-axis force/torque sensor MINI 40 (ATI Industrial Automation), whose normal force resolution is 0.01 N. A Microsoft Kinect sensor (640 × 480 pixel resolution and sample rate of 30 fps) was used to track the position of the hand in three dimensions with the help of the Microsoft Visual C++ OpenCV package. The position accuracy for the Kinect sensor is 1-2 mm. This value was obtained experimentally for an average palpation velocity.

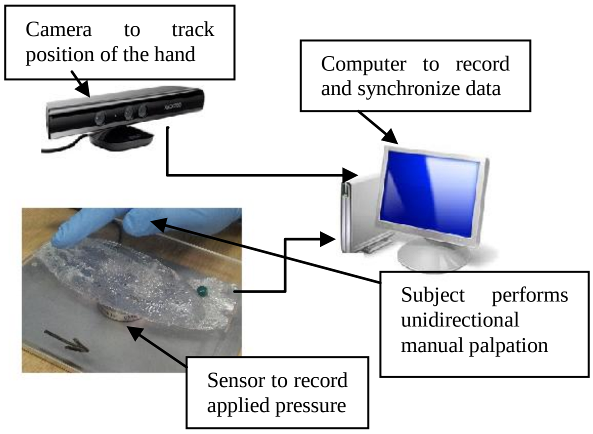

Fig. 1 Schematic representation of the experimental setup

Data processing and statistical analysis was implemented in MATLAB 7.12.0 and R statistics i386 2.15.2 software. A three-way analysis of variance (ANOVA) was used to test the statistical significance of the palpation factors. The confidence level for null hypothesis rejection was set to 95%, for $p < 0.05$.

To understand the responses of soft tissue during various palpation conditions, FE simulations were conducted in ABAQUS 6.10.1. The silicone phantom (50×30 mm^2 planar block) was modelled based on the studies shown in [4]. The size of each finite element was set to 1 mm^2 using a quadrilateral element type. The modelled nodule had a 10 mm diameter and was embedded at two different depths (3 mm, 5 mm) corresponding to the experimental setting. A finger during palpation was modelled as a rigid sphere with a diameter of 20 mm. The modelled soft tissue surface was assumed to be lubricated during palpation experiments; therefore, the contact between simulated tissue and indenting body was set as frictionless. The sphere was indenting the silicone phantom model by 3 mm at the initial step of the FE simulation.

RESULTS

Firstly one needs to test the effect of various palpation factors, such as palpation material, performance of each subject, and applied force and velocity, on the detection rate of hard nodules. Among all factors, the effect of the target material, silicone phantom or ex-vivo organ, was significantly ($F_{(4.00)} = 6.23$, $p < 0.0001$) influencing the detection rate. This result demonstrates that the palpation conditions should be chosen according to the given environment.

This implies that the impact of the traversing velocity should be studied for a given type of target material (for this case - a silicone phantom). Therefore, the ANOVA test is conducted again for the experimental data of palpation for the silicone phantom. It was detected that the used velocity ($F_{(4.24)} = 8.97$, $p < 0.00001$) and the applied force ($F_{(4.24)} = 16.67$, $p < 0.00001$) are significantly influencing the detection rate of hard formations.

The above result supports the importance of correctly chosen force and velocity for soft tissue examination. Thus, it is required to study the influence of the velocity magnitude. According to experimental conditions, the velocity magnitude was subjectively defined by each subject. To exclude individual bias, velocity data for all trials was divided into three groups using k-means clustering. Three clusters are presented in Fig. 2. An overview of detection rates and velocity magnitudes for each cluster and correlation with experimental results is provided in Table I. According to the velocity measurements, the highest detection rate is observed for a slow palpation velocity with a magnitude, which does not exceed 125 mm/s.

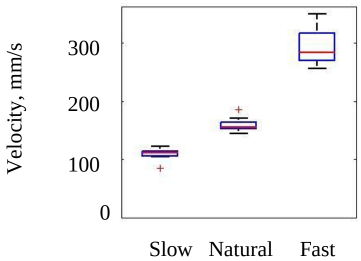

Fig. 2 Clusters of velocity distribution for slow, natural and fast palpation velocity

Table I The impact of palpation velocity

Cluster	Detection Rate %	Velocity Magnitude, mm/s	Correlation with Experiments, %
Slow	87	85 - 123	55
Natural	82	144 - 220	38
Fast	69	256 - 350	75

The experimental measurements of velocity magnitude are used in our FE simulations. Fig. 3 displays the simulated soft tissue model with the deformation above the nodule. The detection rate of a hard nodule depends on the stress magnitude in the target tissue. A subject senses the higher force for the unit area when the stress in the material is higher. Fig. 4 displays the stress magnitude for the indentation contact point for two different depths of the location of a hard nodule. As expected, a slower speed of palpation induces a higher magnitude of stress. A larger depth of the nodule leads to a smaller stress response from the area above it, especially for fast and natural velocity.

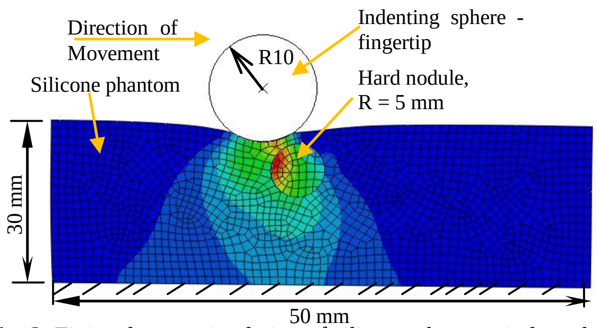

Fig. 3. Finite element simulation of silicone phantom indented with a fingertip above the nodule location (depth 3 mm).

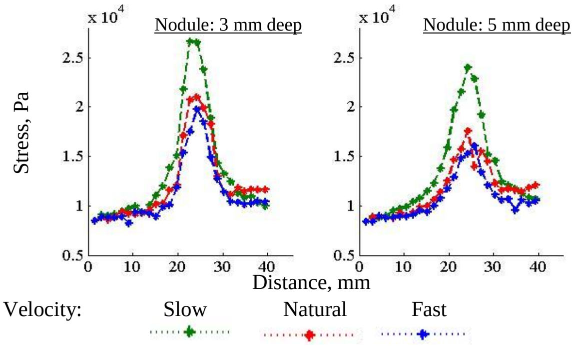

Fig. 4. Stress distribution for different depths of nodules – 3 and 5 mm: (green – slow velocity, red – natural; blue – fast).

CONCLUSIONS

This work underlines the importance of correctly chosen palpation behaviour for a given palpation environment. By means of experimental studies and FE simulations, we have demonstrated the impact of velocity during manual palpation. We believe that these studies will be useful for the creation of advanced probing control strategies, informing developments of tactile sensing methods that can be integrated with RMIS. It is planned to carry out more extensive studies with a tele-manipulation setup in the future.

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