Journal of Medical Robotics Research, Vol. 0, No. 0 (2015) 1–6

Design of a Wearable Fingertip Haptic Device: Investigating Materials of Varying Stiffness for Mapping the Variable Compliance Platform

Samir Morad[a], Zainab Jaffer[b], Sanja Dogramadzi[c]

[a]*Department of Engineering, the University of East London, University Way, London, E16 2RD, UK*
E-mail: s.morad@uel.ac.uk

[b]*Department of Life and Health Science, Aston University, Birmingham, B4 7ET, UK*

[c]*Bristol Robotics Laboratory, University of the West of England, Bristol, BS34 8QZ, UK*

Abstract—Previously, A pneumatic design of a fingertip haptic device (FHD) was developed for virtual reality applications. In this paper, the feasibility of representing tissues of varying stiffness is investigated. Physical properties, stiffness and Young's modulus of the Variable Compliance Platform (VCP) was compared with a set of bolus materials representing soft tissues. The Young's moduli of the bolus materials were 10 times higher than those from the VCP whereas the stiffness was fairly similar. Hence, stiffness is the common parameter that could be used to map the FHD to the bolus materials.

Keywords: surgical robotics, tele-operation, haptics, pneumatic system, bolus materials.

1. Introduction

In recent years, the medical world has seen a lot of advancement which has led to surgeons leaning more towards performing robot-assisted minimally invasive surgery (RAMIS) than open surgeries [1]. The main reason being that RAMIS is less invasive and produces more effective results as it has quicker recovery times and fewer complications for the patient. Surgeons are now able to perform operations without directly looking at or touching the tissues in the body of a patient [2] through the teleoperation of the robot [3].

Tracking or replicating hand/arm motion is an essential part of tele-operation. We interact with our environment mainly using vision and touch. Our hands, with their complex structure, high dexterity and precise manipulation ability are critical instruments in recognizing shape, stiffness and weight of an object [4]. Their high touch sensitivity is achieved due to mechanoreceptors embedded in the surface of the skin. This has created a need for further development of the systems used in minimally invasive surgery (MIS), introducing haptic feedback. Effective feedback is implemented within these systems to provide enough information about the remote body and the teleoperator. This would allow surgeons to 'feel' the tissues during surgery, which is referred to as telepresence [5].

2. Background

Majority of the fingertip haptic devices developed in recent years have been used in virtual environments. With the purpose of providing cutaneous feedback, this type of devices are typically designed using small motors that control force interaction of the cables and/or platforms in contact with the fingertip creating normal or tangential [6]. As most of these devices have been developed for use in virtual environments, the forces they create on the fingertip have not be evaluated against the stiffness of human tissues in in order to be utilised for palpation in robotic surgery. Furthermore, the majority of these devices cannot imitate distinct changes in stiffness to depict different softness levels.

A pneumatic model of a fingertip haptic device (FHD) was previously built and tested in virtual reality [7] by our group. The purpose of this device was to provide haptic feedback to the user, allowing them to perceive different material stiffness in virtual reality. Training new surgeons in virtual reality environments could be a cost-effective substitute and provide a safe environment for trainees to develop their skills.

The purpose of the paper was to try and prove that the FHD, which had previously only been used in virtual reality, could be used to replicate different levels of stiffness similar to different materials. This would allow surgeons to receive haptic feedback during surgery.

Since the model was successful in mapping objects to the FHD in virtual reality, this study aims to explore and map this device to different real tissues using bolus materials of varying stiffness to allow the 'softness' of the materials to be perceived through the FHD. This was done by performing a series of experiments to test the physical properties, like Young's modulus and stiffness, of both the FHD and the tissue like bolus materials, and comparing the results from the two to find a common parameter, which could then be used to map physical properties of the real tissue to the FHD fingertip platform.

3. Materials and Methods

3.1. *Overall design of the Pneumatic FHD*

The first prototype of FHD (Figure 1) was aimed at providing haptic feedback for the varying level of object hardness in virtual reality. This model was built using air as the medium to allow for changes in the levels of stiffness. It consisted of a variable compliance platform (VCP) and its contact with the finger which was controlled by servo motors, using a rack and pinion mechanism (RP), to allow the platform to undergo linear motion and position the finger. A syringe mechanism to pump air into and out of the inflatable surface controlled the VCP stiffness [8].

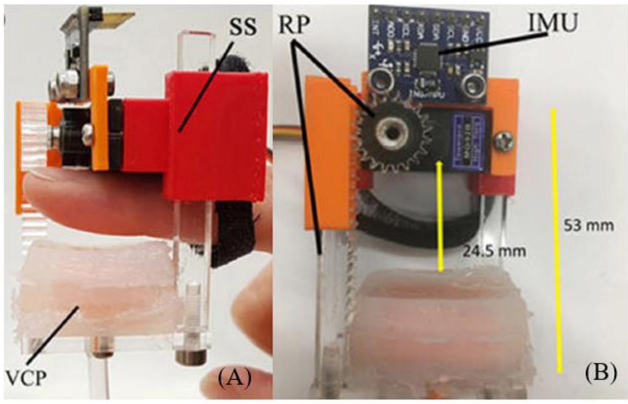

Fig. 1. FHD, (A) side view with an index finger placed against the support structure (SS) and held with a flexible strap; the RP mechanism lies behind the finger and the VCP below the finger, which can linearly move along the RP closer/farther from the finger, (B) front views with the maximum VCP displacement; Inertial Measurement Units (IMU) sensors used for motion tracking.

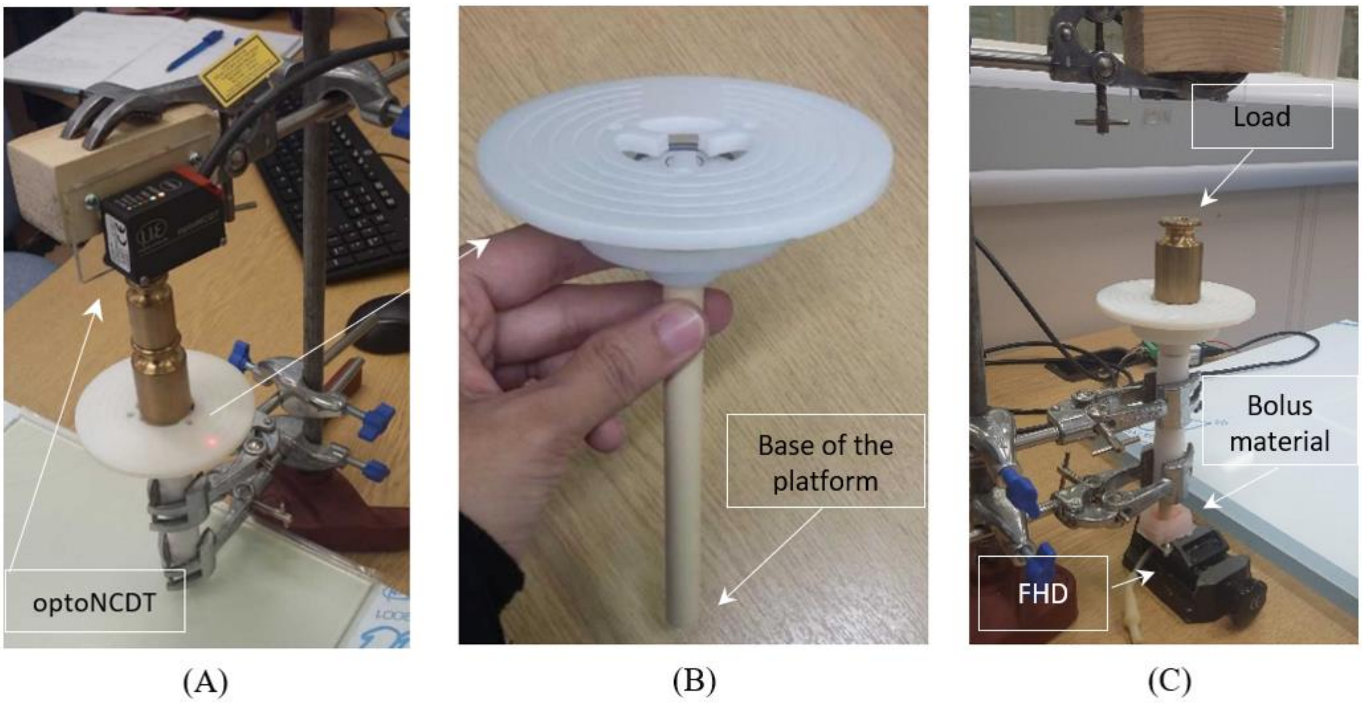

Fig. 2. Experimental setup. (A) optoNCDT laser sensor is used to measure the changes in displacement when masses are loaded onto the bolus materials. (B) 3D printed platform with bubble spirit level. (C) optoNCDT laser sensor is used to measure the changes in displacement when masses are loaded onto the FHD.

3.2. *The experimental setup*

The physical properties of the FHD and a set of three bolus materials were tested and analyzed to find a common parameter to map the materials to the FHD.

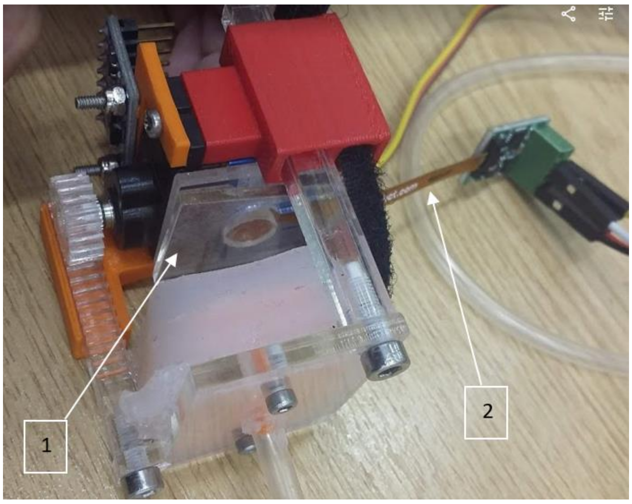

Fig. 3. FHD, (1) 3D printed part to secure the pressure sensor. (2) single tact pressure sensor.

A 3D printed platform with a bubble spirit level to ensure that it was flat on the surface of each material (Figure. 2-B) was utilized for this experiment. The optoNCDT 1420 laser sensor (Figure. 2-A) was used to measure the change in displacement due to indentation of the material as different masses were added to the surface of the 3D printed platform. The laser was targeted at the flat surface of the 3D printed platform.

For each material, weights in the range of 50g to 400g were added to the 3D printed platform for a period of 30 seconds, after which the value from the laser sensor was recorded. Figure 2 displays the experimental setup.

The loadings for each material were repeated four times and the average displacement was calculated. A graph of weight against the average displacement was plotted for each material. The average displacement was used to calculate the stress and strain of the three bolus materials and a graph of the two was plotted to obtain the Young's modulus for each material. The entire process was repeated with the FHD to obtain values for the Young's moduli of the FHD at different volume levels.

3.3. *Determining the stiffness*

The experimental setup in Figure. 2-A was used to determine the stiffness of three bolus materials and of the FHD at different volume levels.

The three bolus materials were cut to a diameter of 10mm to and placed at the base of the 3D printed part in Figure 2-B. The experiments were repeated on the smaller-sized materials and the new young's moduli for the materials recorded.

We evaluated the non-linearities of the force-displacement response through the identified hysteresis curves (Figure 4 and 5). Considering the small exhibited hysteresis we opted for a linear model of the stress-strain relationship.

The experiment was performed on the materials and the stiffness (k) was calculated for the materials and the FHD using

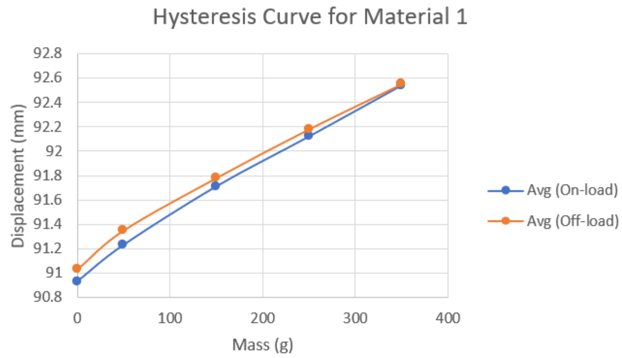

Fig. 4. the Hysteresis Curve for Material 1.

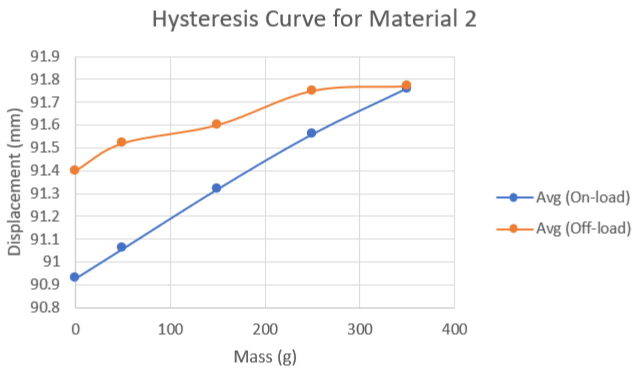

Fig. 5. the Hysteresis Curve for Material 2.

equation (1):

$$k = F/\delta \quad (1)$$

Where F is the force applied (N) and δ is the change in displacement (m).

3.4. *Forces applied on the fingertip*

The SingleTact pressure sensor is used to measure the forces acting on the finger when in the FHD. Figure 3 displays the circuit connections made in this FHD. To allow the pressure sensor to be secured to the FHD, two small platforms, as seen in Figure 3, were 3D printed.

The entire procedure was repeated with increasing the volume of air in the inflating surface in an interval of 1ml from 1-5ml. Each reading was repeated 4 times, and the values averaged to get accurate results.

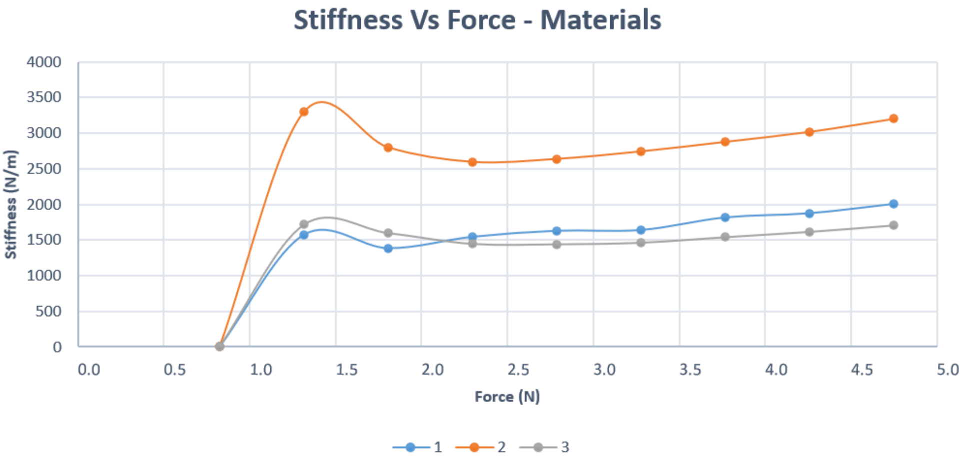

Fig. 6. Graph of Stiffness against Force for the three bolus materials

4. Results and Discussion

The FHD stiffness representation is characterized in terms of resulting pressure and force applied to the fingertip created through the relationship of the two functional parameters – pressure and displacement of VCP.

4.1. *Modulus of elasticity*

The gradient of a Stress-Strain graph represents the Young's modulus. On comparing the Young's moduli of the materials to that of the different volume levels in the FHD, it was realized that the two could not be mapped. The Young's moduli of the materials (Table 1) are much greater (up to 10 times higher) than those from all the different levels of the FHD stiffness (Table 2). Had the values of the Young's moduli from the materials been similar to those from the FHD, it would have been possible to match certain levels of the FHD to some materials i.e., the levels on the FHD would imitate the different materials.

This proved that the Young's modulus is not a common parameter that can be used to map the materials to the FHD.

An interesting observation from this data is that the young's modulus of the softest bolus material (material 1) is quite similar to that of a human meniscus. According to Sweigart et al. [10], the Young's modulus of a human meniscus is between 100-160kPa depending on whether it is the anterior or posterior side of the meniscus.

4.2. *Stiffness*

On comparing the values of the stiffness of the materials (Figure 6) to that of the different levels on the FHD (Figure 8), it was noticed that there is a similarity. They do not have the same values; however, they are quite similar suggesting that stiffness can be used as a common parameter to map the materials to the FHD.

Furthermore, research suggests that stiffness is a property of a particular object whereas Young's modulus is a property of the material.

4.3. *Forces applied on the fingertip*

The SingleTact force sensor readings were converted to force (in Newton) equating to a minimum value of 5.04N and a maximum value of 7.01N.

As the VCP moves closer to the roof of the FHD, it applies more force on the finger. This would change the perception of the inflating surface for the user, allowing the user to 'feel' the difference in stiffness.

From the graph in Figure 7, it can be concluded that the higher the volume of air in the inflating surface, the greater the forces applied by the VCP.

Table 1. Young's Moduli of the bolus materials

Material	Young's Modulus (MPa)
1	0.1035
2	0.1714
3	0.1847

Table 2. Young's Moduli of the different volume levels in the FHD

Volume (ml)	Young's Modulus (MPa)
1	0.0247
2	0.0289
3	0.0324
4	0.0359
5	0.0386

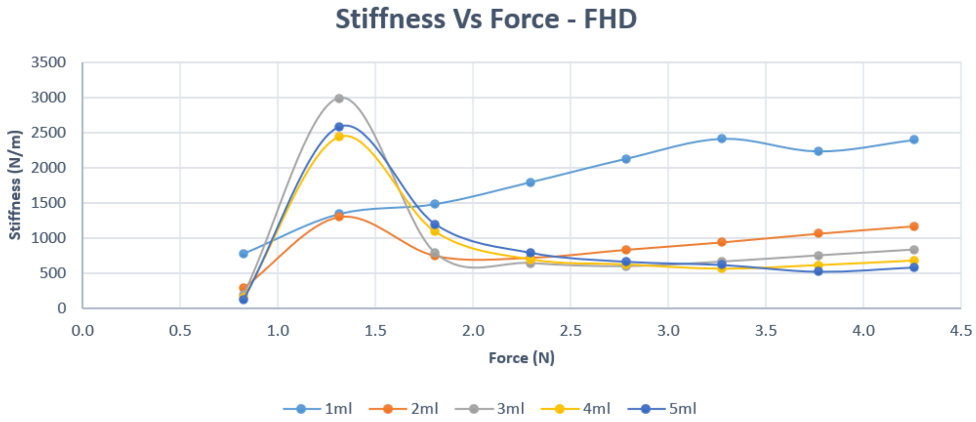

Fig. 7. Graph of Stiffness against Force at the different volume levels in the FHD

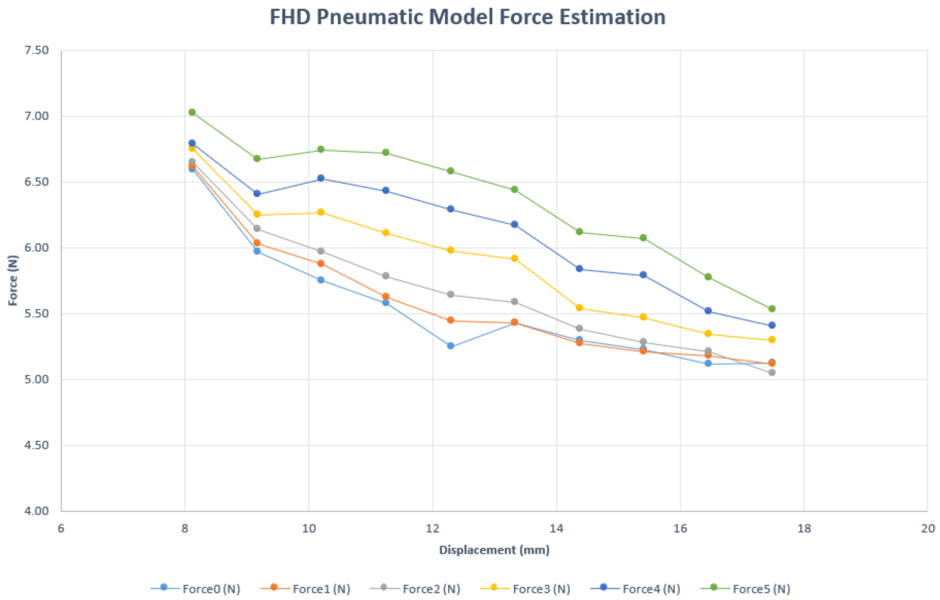

Fig. 8. Graph of Changes in Force on Index Finger with Linear Displacement of the VCP

5. Conclusion

Previously, a pneumatic design of a FHD was developed for virtual reality applications.

Upon investigating the physical properties of both the pneumatic model of the FHD and the bolus materials, it was concluded that stiffness, rather than Young's modulus, was a common parameter and could be used to map the two. Research also proved that the Young's modulus is a material property rather than the property of a device and thus was not ideal for the mapping. Interestingly, the Young's moduli of the bolus materials were very similar to that of a human meniscus.

In the future, we will use a variety of fingertips to experimentally test the FHD confirm our initial findings. Also, we will redesign the FHD to produce a new mechanical model which can be mapped to a human meniscus, thus allowing surgeons to 'feel' the stiffness of the tissue during robotic orthopedic surgery.

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Samir Morad received the BEng degree in medical engineering from Queen Mary College, University of London, London, UK, in 2010 and the MSc. degree in biomedical engineering from Imperial College London, London, UK, in 2011, and PhD. degree in medical robotics from Imperial College London, London, UK, in 2015. He is currently a lecturer in mechanical engineering and the leader of the biomedical engineering programme at the department of architecture, computing and engineering at the University of East London.

From 2016 to 2019 Dr Morad was a teaching associate in biomedical engineering at the department of life and health science at Aston University.

From 2015 to 2016 Dr. Morad was a Research Fellow in medical robotics at Bristol Robotics Laboratory. His research interest includes the development of robot assisted flexible surgical intervention, 3D reconstruction and FEA analysis of human tissues.

Sanja Dogramadzi received her MEng degree in Mechatronics, robotics, and automation Engineering from the University of Belgrade, Serbia, and her Ph.D. degree robotic endoscopy from the University of Newcastle upon Tyne, UK. She is currently Professor of Medical Robotics and Intelligent Healthcare Technologies at the Department of Automatic Control and Systems Engineering at the University of Sheffield.

From 2002 to 2006, Prof Dogramadzi was at the University of Leeds, as Research Fellow, and from 2006 to 2020 she was at Bristol Robotics Laboratory, University of the West of England, as Senior lecturer /Associate/Full Professor.

Sanja Dogramadzi is the author of over 127 publications. Her research interests include design and control of surgical robots for minimally invasive fracture surgery and robot-assisted MIS, rehabilitation robots, physical assistance robots and safe and ethical human-robot interaction. She has led and coordinated many research projects funded by UK councils, Innovate UK, NIHR and European Commission.

Zainab Jaffer received her MEng degree in Biomedical Engineering from Aston University, UK.

From 2018 to 2019, Zainab was at Bristol Robotics Laboratory, as an internship, as part of her Meng project, working on SMARTsurg Project.