Proceedings Paper:

Fakhoury, E, Culmer, P orcid.org/0000-0003-2867-0420 and Henson, B orcid.org/0000-0003-0933-1722 (2018) The impact of visual cues on haptic compliance discrimination using a pseudo-haptic robotic system. In: Proceedings of the 2017 IEEE International Conference on Robotics and Biomimetics. 2017 IEEE International Conference on Robotics and Biomimetics (ROBIO), 05-08 Dec 2017, Macau, China. IEEE , pp. 1719-1725. ISBN 978-1-5386-3742-5

https://doi.org/10.1109/ROBIO.2017.8324666

The Impact of Visual Cues on Haptic Compliance Discrimination Using a Pseudo-Haptic Robotic System

Evan Fakhoury, Peter Culmer, Brian Henson

Abstract

A psychophysical magnitude estimation experiment was set up to determine the extent of the contribution of visual feedback during haptic compliance discrimination. Subjects remotely palpated physical compliant samples using a novel pseudo-haptic feedback system which allowed for independent manipulation of visual and haptic feedback. Subjects were asked to rate the compliance of a test sample based on that of a reference sample. While visual feedback was modified by switching the physical test samples shown to participants during indentation, haptic compliance of the test samples was always identical to that of the reference sample. Any variations in haptic sensation was a result of pseudo-haptic illusions. Ratings were collated and fitted to Steven's power law as well as Weber's law. A 0.18 power exponent suggests that the system was successful in generating viscoelastic properties through variations in visual information only. A 19.6% visual change from the reference compliance was necessary in order to perceive a change in haptic compliance using the pseudo-haptic system. These findings could prove beneficial in research and educational facilities where advanced force feedback devices are limited or inaccessible, where the concept of pseudo-haptics could be used to simulate various mechanical properties of virtual tissue for training purposes without the need for complicated or costly force feedback.

I. INTRODUCTION

Current surgical training systems have the benefit of providing medical students and novice surgeons with a realistic experience similar to that of a real operating theatre in a safe and controlled virtual environment [1]. While effective, these systems are not accessible to all hospitals and teaching facilities due to their high cost. Off the shelf haptic feedback devices such the Omega.7 (Force Dimension) can be used to design and assemble similar surgical trailing systems. However, this would require some expertise in software and hardware design and programming. While these devices are relatively inexpensive, their accuracy and force output are usually limited [2].

Visual feedback has been shown to dominate over haptic feedback in compliance discrimination tasks [3]–[5]. The scope of this visual dominance, however, specifically in compliance discrimination tasks requiring the use of a tool such as the case of LS and RALS, is yet to be determined. In order to accomplish this task, the concept of 'pseudo-haptics' was used. Pseudo-haptics is the generation, augmentation, or deformation of haptic sensations by information from other sensory modalities [6]. Pragmatically, it is the process of simulating a haptic sensation by manipulating the visual information available.

Researchers have shown the potential of pseudo-haptics in generating several haptic sensations [7]–[13]. However, the extent of that potential, specifically within the context of surgical technologies, remains unknown. The aim in this paper is to determine the extent to which visual feedback augmentations can generate haptic sensations using pseudo-haptics. By independently controlling the visual and haptic information presented to participants, it becomes possible to identify the human visual boundaries, or limitations, of illusion. Such information can be applied onto laparoscopic simulators and haptic feedback devices to simulate greater force ranges, reduce errors, and enhance accuracy.

II. PREVIOUS WORK

Srinivasan et al. [3] investigated the impact of visual information on the haptic perception of stiffness in virtual environments. Using a force reflective haptic interface, they set up two-alternative forced-choice (2AFC) experiments in which participants pressed pairs of virtual springs and were asked to choose which virtual spring felt stiffer. While haptic information was provided using the force feedback device, visual feedback was represented graphically on a computer monitor. The results indicated the presence of a haptic 'illusion': a distortion of haptic stiffness which increased as the mismatch between visual and haptic feedback increased. It was suggested that such illusions can be exploited in the future in order to overcome haptic interface limitations as well as enhancing the range of haptic experiences. However, these illusions can also be used to simulate new sensations and not just enhance existing ones.

To date, pseudo-haptics has been used to simulate numerous haptic properties such as stiffness of a virtual spring [9], texture of an image [16], friction in a virtual passage [17], mass of a virtual object [18], torque feedback [19] and shapes of different objects [12]. However, it has not yet been used to simulate the viscoelastic behaviour of compliant objects such as human tissue.

Lecuyer et al. [6] used a passive isometric device to generate a pseudo-haptic effect. While isometric devices do not provide the user with force feedback, pseudo-haptics was used to create the illusion of a force by providing participants with on-screen virtual spring which behaved as normal springs would while they pressed on the isometric device. A 2AFC compliance discrimination task was set up between a virtual spring simulated using the isometric device and a real spring with equivalent compliance. A 13.4% just-noticeable difference (JND) which falls between the 8-22% previously found by Tan et al. [20] suggests consistent manual discrimination of compliance using a passive input device. However, using a force feedback device instead of an isometric one to perform compliance discrimination tasks between virtual and real stimuli has not yet been investigated.

Lecuyer et al. [9] attempted to identify the 'boundary of illusion' occurring during pseudo-haptic feedback. A force feedback device (PHANToM™) was used to simulate the stiffness of two virtual springs. Within each pair of virtual springs presented, one had matching visual and haptic displacement behaviour while the other had either haptic or visual bias. While participants were able to discriminate compliance using the pseudo-haptic feedback system, their responses were often inconsistent. The authors demonstrated the capability of virtual visual feedback to distort perception of simulated haptic spring stiffness. However, it is still unknown whether visual feedback in the form of real stimuli can distort the perception of simulated haptic stiffness. The significance of such an investigation is evident in robotic-assisted laparoscopic surgery (RALS) and RALS training where either real or simulated viscoelastic tissue is remotely manipulated using a haptic feedback system.

III. METHODS

A magnitude estimation experiment was designed to quantitatively determine the contribution of visual feedback during haptic discrimination of compliance using a novel robotic pseudo-haptic system. Participants rated the softness of stimuli based on that of a reference stimulus with known softness rating.

A. Pseudo-haptic System Design

The system consisted of:

- Three 6-axis commercial robots (VS-068, Denso Robotics)
- An HD webcam (C920, Logitech)
- A 7 DoF haptic feedback device (Omega.7, Force Dimension)
- A desktop computer that controls and links every component in the system together using a custom program via LabVIEW software (National Instruments).

The authors of this paper designed the experimental setup and the system requirements. The technical programming of the system, however, was performed by *Re-Solve Research Engineering Ltd*. A schematic of the pseudo-haptic system is shown in Figure 1. A flow chart describing the process of visio-haptic separation during an experiment is shown in Figure 2.

1) Visual Feedback

Visual feedback during indentation is provided through a 2D computer monitor. Physical samples located within the robotic setup away from the participant are interchanged by rotating a circular tray, allowing for a visual change in sample compliance. An HD webcam (C920, Logitech), with a 1920x1080 resolution comparable to that of laparoscopic cameras was fixed facing the indenter at an angle mimicking indentation using direct visual access to the samples. The disc holding the samples was mounted onto another robot which rotates based on which sample was to be indented. Eleven pre-set angular rotation values each corresponding to a sample were used to control the positions to which the robot moves. Since haptic and visual cues were separated from one another, participants used the Omega.7 to indent Voigt model representations of the physical samples while observing those physical samples on a computer monitor. Video frame size was adjusted such that the samples appear having the same size as if directly observing them while seated. A frame rate of 30 fps was sufficient to allow for smooth uninterrupted video. The position of the indenter robot was governed by that of the Omega.7 end effector, which in turn was controlled by the participants.

2) Force Feedback

The system provides force feedback through the Omega.7 haptic feedback device. A Voigt model for each physical sample was used to estimate their corresponding stiffness (E) and damping (η) coefficients. These coefficients were then used to control the force feedback provided by the Omega.7 while participants indented the samples. In this set-up, participants moved the tool connected to the end effector of the Omega.7. The position of the Omega.7 was sent to the robot indenter arm, which in turn mimicked the position and speed of the Omega.7.

B. Participants

Thirty-two participants (16 male and 16 female) took part in this study. None of them had any known hand or eyesight impairments according to a completed questionnaire. Participants were undergraduate students, postgraduate students and staff at the University of Leeds with ages ranging between 18 and 37. Participants were naïve to the aims of the experiment, without any medical background. Ethical approval was obtained before commencing the experiment.

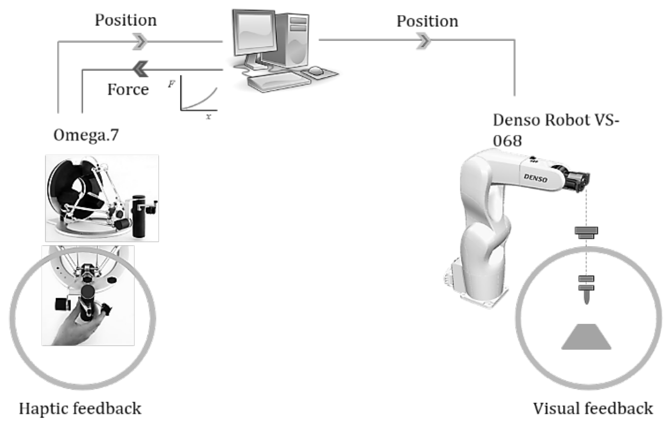

Figure 1. Pseudo-haptic feedback system design and set-up

C. Stimuli

Eleven silicone samples were fabricated for this experiment. Stress-strain data of each sample were obtained using a custom built indentation rig. The data was fitted to a Voigt viscoelastic model to obtain stiffness constants and damping coefficients for the samples. Stimuli fabrication, compliance testing and model fitting methods are extracted from [4], [5].

1) Fabrication

The samples were fabricated using a two-part silicone-based gel polymer (Plastil, Mouldlife) with a plasticizer in different ratios to obtain the desired compliance levels. Plastil gel 10 parts A and B were mixed with the plasticizer in a ratio of A: B: plasticizer ranging from 1:1:2.6 (hardest) to 1:1:4 (softest) to create 11 samples. A silicone mould tray was used to cast each sample. Each tray cup was 5cm wide and 2cm deep with a truncated conical shape. Prior to pouring the silicone mixtures, each cup was sprayed three times with a thin polyurethane coating to prevent sticking and to maintain the same adhesion and friction properties across all the samples. The coatings were sprayed onto the moulds using an airbrush. After allowing the coatings to dry for approximately 15 minutes, a unique ratio of Plastil gel 10 parts A, B, and plasticizer for each sample were poured into plastic containers and mixed thoroughly before pouring into the silicone tray cups. A skin coloured pigment was also added into each mixture without affecting the material properties to mask visual cues from slight colour variations of each sample. The silicone samples were left for 24 hours to set and then coated with a layer of thin polyurethane to prevent the surface from sticking to any object after removal. Samples were then carefully removed from the mould tray and were ready to be tested.

2) Compliance Testing

The samples were tested using a bespoke indentation rig which consisted of a linear actuator (SMAC Inc. USA, LCA50-025-7) coupled with a 6 degree-of-freedom (6-DOF) force transducer (ATI, Nano17). Aluminium framework (Bosch Rexroth) was used for the structure. Force and position data were controlled and measured using a LabVIEW (National Instruments, TX) program. A hemispherical unplasticized polyvinyl chloride rigid tip with an 8 mm diameter indented the stimuli at a rate of 10mm/s until reaching a depth of 10 mm into the stimuli. The force-displacement profile of the indentation was recorded at a sampling rate of 1 kHz. Each sample was tested five times. The average force and displacement values across the five repeats were calculated and used for model fitting.

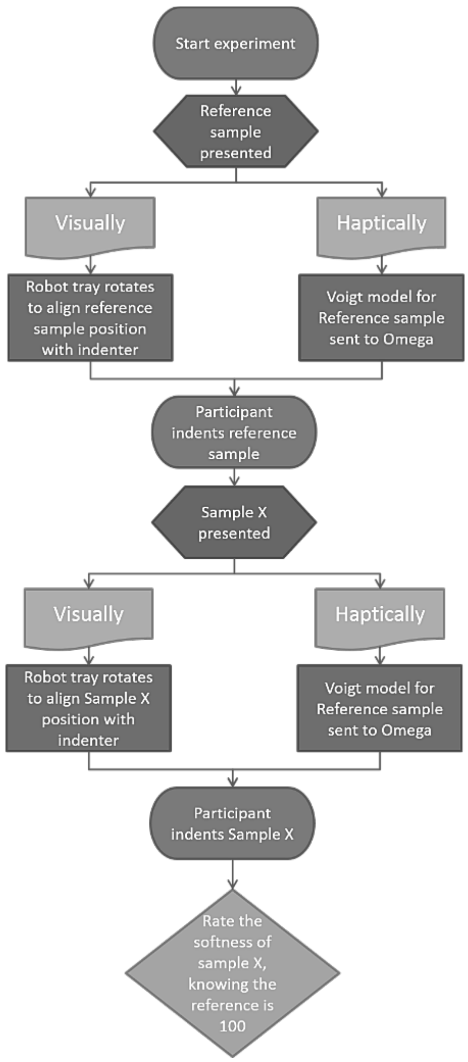

Figure 2. Flow chart describing the process occurring within the pseudo-haptic system during an indentation task

3) Viscoelastic Model Fitting

The Voigt model [Equation (1)] was used in this experiment as it has been used in the literature to model the behaviour of soft tissue during loading [4], [21].

$$\varepsilon = \frac{\sigma}{E}[1 - e^{\frac{-Et}{\eta}}] \quad (1)$$

Where ε is the total strain, σ is the total stress, E is the Elastic modulus, η is the damping coefficient and t is the instantaneous time during loading.

Force and position data for all 11 samples obtained during the indentation tests were fitted to the Voigt model. The stiffness and damping coefficients are identical to those obtained in previous experiments [4].

D. Experiment Design

Participants took part in a magnitude estimation experiment in which they were asked to assign numeric values to the softness of a test sample based on a reference sample with pre-set fixed softness rating. Within each presented pair, participants used the end effector stylus tool to move the robot arm which in turn indented the samples. Participants had indirect visual access to the indentation process through a computer screen which relayed a live feed from a HD webcam mounted near the indenter robot. Participants were asked to first indent the reference sample which was assigned a unit-less subjective softness value of 100, while observing the indentation process on the screen in front of them. They were then asked to perform the same indentation process on the test sample. After participants were finished indenting both samples, they were asked to assign a softness rating value to the test sample, based on that for the reference sample.

E. Experiment Procedure

Reference Sample Indentation

Participants were asked to hold the stylus in front of them with their dominant hand as they would hold a pen. Moving the stylus up and down moves an on-screen hemispherical shape located on the right hand side of the screen. This shape represented the indenter tip attached to the robotic system and is an illustration of the position and speed of the indenter tip, as seen in Figure 3. On the right hand side of the screen, an interactive diagram was created to allow the participant when to start palpating, where to start from, how deep to palpate the sample, and at what rate. On the left hand side of the screen, the physical sample is displayed using an HD webcam attached to a robotic arm facing the indenter tip. Moving the stylus with their hand, participants moved the on-screen tip to the initial position at the top of the illustration. Participants lowered the tip until they reached the top of the green shaded region simulating the surface of the presented sample.

Participants were told that the reference sample they were about to indent is given a softness rating value of 100. They were asked to indent the reference sample actively trying to follow the moving horizontal line. This line was an indication of the speed of palpation as well as the maximum depth necessary to register a valid palpation attempt. While continuing to indent the reference sample, participants were asked to shift their vision to the left hand side of the screen and observe the physical stimulus being indented. Participants were asked to use both visual and haptic information available to 'have a feel' for the softness of the sample and try to associate the softness of this sample to the value of 100 given earlier. Participants were allowed to palpate as many times as needed. They were asked to move the on-screen tip back to the initial position.

Test Sample Indentation

At that point, the haptic feedback system automatically switches to the test sample while the screen blacks out to prevent the participants from seeing the samples being changed in the robotic system. After the test sample was ready for palpation, a test sample in the pair appeared on the screen and the participant could indent the sample as previously demonstrated.

Test Sample Rating

After indenting the test sample, participants were asked to assign a softness rating value to this test sample based on that assigned to the reference sample. For instance, if they felt the test sample was twice as soft as the reference sample, then they would say 200. If they felt the test sample was half as soft as the reference, they would say 50.

There was no upper or lower limit on ratings and there was no time limit. The participants responded verbally by stating the softness value they assigned to each presented test sample. If unsure of what rating to provide, participants could ask for the reference and test samples to be presented again. After the pair was completed, the participants' rating was recorded and the system automatically moved on to the next pair on the list.

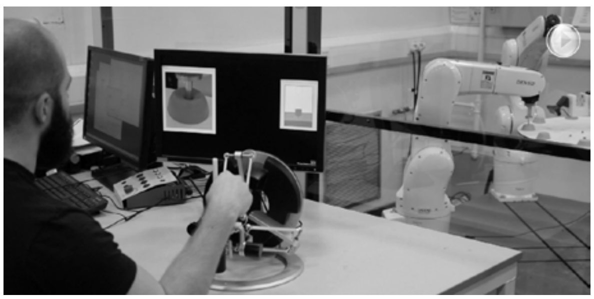

Figure 3. Experiment setup

General Information

Each pair started with the same reference sample followed by a test sample. Each participant was presented with 10 pairs in random order repeated 10 times each in random order as well. Pairs consisted of a reference sample with defined viscoelastic stiffness and damping as well as a test sample which changes randomly from a pair to the next. In total, 10 test samples with different levels of compliance were used in this experiment. The order within each pair was randomized as well to prevent extraneous factors from affecting the results.

F. Experimental Analysis

Weber's law [Equation (2)] was used to interpret the participants' responses. Weber's law, which has been used in the literature to analyse performance during compliance discrimination tasks [22]–[24], is defined as the relationship between the stimulus intensity level (Φ) and the magnitude of the difference threshold (ΔΦ) through a constant fraction (c) [25].

$$\Delta\Phi = c\,\Phi \qquad (2)$$

Participants' ratings were also fitted to Steven's power law. The power law is a psychophysical relationship between the physical magnitude of a stimulus and its perceived intensity [26]. Because it describes a broader range of sensations, the power law often replaces Weber's law in psychophysical analyses [26]. Steven's power law is governed by Equation (3) as follows:

$$\Psi = k\,\Phi^{a} \qquad (3)$$

Where Ψ is the sensation magnitude, Φ is the stimulus intensity, k is a constant which determines the scale unit, and a is the power exponent which varies depending on the stimulus sensory type. Using the participants' ratings to calculate Ψ values, and substituting the stiffness values for Φ values, the power exponent (a) can then be estimated over the range of samples.

IV. RESULTS

Table 1 shows the compliance of each physical sample, along with the theoretical ratings, the participants' ratings, and the standard deviations corresponding to the participants' ratings. The average participant ratings were obtained by calculating the median of all participant ratings for each test sample. Using the stiffness of the samples, theoretical ratings based on the reference rating of 100 were calculated. These ratings express the compliance of the samples in the same unit as the participants' ratings. The theoretical values (visual compliance) were compared to the participants' ratings (perceived haptic compliance) to obtain the visual 'boundaries of illusion'. The perceived haptic compliance based on a range of visual compliance levels is observed in Figure 4. Fitting both sets of data to a linear trend line, it is possible to estimate the slope or rate of change of each.

Compliance values were obtained by calculating the inverse of each stiffness value. The stiffness-based ratings were tabulated for comparison purpose only. These ratings reflect the compliance levels of the physical stimuli, not the participant responses. The ratings were obtained using Equation [4].

$$R_i = \frac{C_i - C_{ref}}{C_{ref}} \text{ x } 100 \qquad (4)$$

Where C_i the compliance of the selected sample and C_{ref} is the reference compliance.

These ratings express the compliance of the samples in the same unit as the participants' ratings. The theoretical ratings were compared to the participants' ratings to obtain the visual 'boundaries of illusion'. Finally, participants' responses were collected and used to calculate the power exponent corresponding to Steven's power law.

Table 1. Stiffness, theoretical softness rating and mean participant rating for each sample

Sample	1	2	3	4	5	6	7	8	9	10	11
Stiffness (N/mm)	0.298	0.278	0.257	0.246	0.235	0.23	0.22	0.209	0.199	0.1857	0.179
Compliance (mm/N)	3.35	3.59	3.89	4.06	4.24	4.33	4.55	4.77	5.01	5.39	5.58
Theoretical ratings	77.3	82.9	89.8	93.7	97.9	100	105	110	116	124	129
Participant ratings	98.01	100.3	100.5	99.8	101.0	100	106.4	103.7	104.9	106.6	108.1
Standard deviation	14.39	15.23	13.48	14.14	15.11	-	16.79	15.34	14.53	15.14	16.77

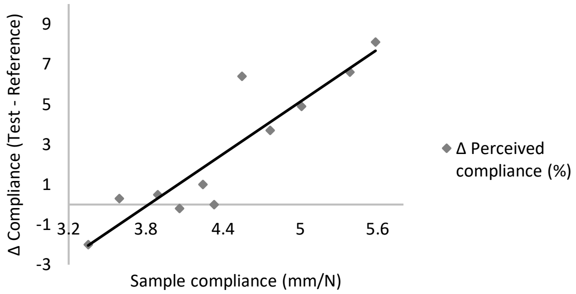

Figure 4. Differences in perceived haptic compliance between reference and test samples

Throughout the experiment, physical samples were interchanged in order to simulate several visual compliance levels. Hence, the data describing the change in visual compliance matched that of the physical sample compliance with a one to one ratio. However, the perceived haptic compliance represents collated participants' responses corresponding to visually induced changes in haptic sensation. An estimate of the slope of the trend line fitted to the data suggests that in order to perceive a change in haptic compliance using the pseudo-haptic system, a 19.6% visual change from the reference compliance is necessary. This value represents the estimated Weber fraction for compliance discrimination using a pseudo-haptic feedback system. Figure 5 shows the distribution of the Weber fractions as well as the Stevens power exponents calculated for each participant based on their unique responses. Sample compliance and participants' softness ratings were used to calculate Steven's power exponent. Fitting the collated ratings to Steven's power law function, k and a constants are estimated. This function [Equation (4)] is shown below.

$$\Psi = 78.2\, \Phi^{0.18} \qquad (5)$$

A 0.18 power exponent obtained through compliance discrimination using the pseudo-haptic system which is less than one implies that this is a negatively accelerated or compressive function. Nevertheless, a positive power exponent value suggests that the simulation of haptic sensations via visual alterations is possible.

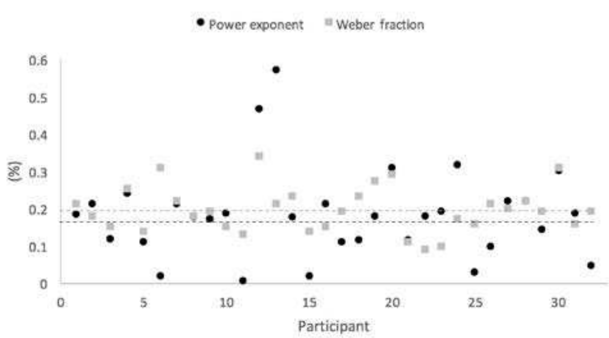

Figure 5. Distribution of Weber fractions and Steven's power constants across all the participants, with the dotted lines representing the group means

V. DISCUSSION

The pseudo-haptic system used in this experiment applied a viscoelastic (spring-damper system) model to simulate haptic compliance. Previous researchers have assessed the potential of pseudo-haptics for the generation and augmentation of haptic sensations such as stiffness [8], [9], [11], [28]. None have done so, however, for the compliance of tissue during palpation. The literature has shown that the Weber fractions for compliance discrimination of deformable objects using haptic interfaces range from 14 to 25%. With a 19.6% Weber fraction which falls within the range from previous work, results from this paper suggest that by modifying visual cues during haptic indentation, it is possible to simulate new sensations of haptic compliance.

Unlike previously obtained exponents [27], the relationship reported here predicts haptic softness magnitude based on variations in visual cues only. Using the obtained constant k and a, it is possible to predict the softness sensation magnitude of any compliance intensity. In this paper, a finite number of physical samples was used. The power function can be used to predict performance at larger and smaller compliance levels that are otherwise troublesome to fabricate.

VI. CONCLUSION AND FUTURE WORK

The concept of pseudo-haptics was put to use in order to determine the extent of the visual impact on haptic discrimination of compliance. Participants' ratings were collated and fitted to Steven's power function. A 0.18 power exponent suggests that the system was successful in generating viscoelastic properties through variations in visual information only. Moreover, in order to perceive a change in haptic compliance using the pseudo-haptic system, a 19.6% visual change from the reference compliance is necessary.

The pseudo-haptic system described in this paper has been shown to generate haptic sensations through augmentation of visual information. Future work will focus on using pseudo-haptics to determine the degree of impact of visual information during more complex MIS tasks such as suturing and needle insertion. Moreover, by combining compliance analysis conducted in this paper with human and object mapping into avatars as discussed by [23], the system could be used to simulate physical interactive activities. Virtual activities such as press-ups, pull-ups, and contact sports could possibly be simulated.

While passive systems such as a computer mouse or a joystick have been used in the literature to simulate haptic sensations [8], [10], [28], [30], the results show the potential for integrating pseudo-haptics into active haptic feedback systems. Pseudo-haptics can be incorporated into standard off-the-shelf haptic feedback devices in order to enhance force ranges or reduce error without adding any added hardware costs. Alternatively, these relatively inexpensive haptic feedback devices are difficult to modify mechanically or electronically as they have fixed specifications, workspaces, and force outputs and are not suitable for customisation.

REFERENCES

[1] F. L. Ferrufino, J. V. Cohen, E. B. Schaffner, F. C. Eulufi, F. P. Müller, J. M. Castillo, N. J. Cassis, and C. B. Wilson, "Simulation in Laparoscopic Surgery," *Cir. Esp. Engl. Ed.*, vol. 93, no. 1, pp. 4–11, 2015.

[2] T. R. Coles, D. Meglan, and N. W. John, "The role of haptics in medical training simulators: a survey of the state of the art," *Haptics IEEE Trans. On*, vol. 4, no. 1, pp. 51–66, 2011.

[3] M. A. Srinivasan, G. L. Beauregard, and D. L. Brock, "The impact of visual information on the haptic perception of stiffness in virtual environments," in *ASME Winter Annual Meeting*, 1996, vol. 165.

[4] E. Fakhoury, P. R. Culmer, and B. Henson, “The effect of indentation force and displacement on visual perception of compliance,” in *World Haptics Conference (WHC), 2015 IEEE*, 2015, pp. 88–93.

[5] E. Fakhoury, P. Culmer, and B. Henson, “The Effect of Vision on Discrimination of Compliance Using a Tool,” *Int. J. Hum.-Comput. Interact.*, vol. 30, no. 11, pp. 882–890, 2014.

[6] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, “Pseudo-haptic feedback: Can isometric input devices simulate force feedback?,” in *Virtual Reality, 2000. Proceedings. IEEE*, 2000, pp. 83–90.

[7] A. Lecuyer, L. George, and M. Marchal, “Toward Adaptive VR Simulators Combining Visual, Haptic, and Brain-Computer Interfaces,” *Comput. Graph. Appl. IEEE*, vol. 33, no. 5, pp. 18–23, 2013.

[8] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, “Pseudo-haptic feedback: can isometric input devices simulate force feedback?,” in *Virtual Reality, 2000. Proceedings. IEEE*, 2000, pp. 83–90.

[9] A. Lécuyer, J.-M. Burkhardt, S. Coquillart, and P. Coiffet, “‘ Boundary of illusion’: an experiment of sensory integration with a pseudo-haptic system,” in *Virtual Reality, 2001. Proceedings. IEEE*, 2001, pp. 115–122.

[10] F. Argelaguet, D. A. G. Jáuregui, M. Marchal, and A. Lécuyer, “Elastic images: Perceiving local elasticity of images through a novel pseudo-haptic deformation effect,” *ACM Trans. Appl. Percept. TAP*, vol. 10, no. 3, p. 17, 2013.

[11] F. Argelaguet, T. Sato, T. Duval, Y. Kitamura, and A. Lécuyer, “Collaborative Pseudo-Haptics: Two-User Stiffness Discrimination Based on Visual Feedback,” in *Haptics: Neuroscience, Devices, Modeling, and Applications*, Springer, 2014, pp. 49–54.

[12] Y. Ban, T. Kajinami, T. Narumi, T. Tanikawa, and M. Hirose, “Modifying an identified curved surface shape using pseudo-haptic effect,” in *Haptics Symposium (HAPTICS), 2012 IEEE*, 2012, pp. 211–216.

[13] F. Crison, A. Lécuyer, A. Savary, D. Mellet-d’Huart, J.-M. Burkhardt, and J.-L. Dautin, “The use of haptic and pseudo-haptic feedback for the technical training of milling,” in *EuroHaptics Conference poster, Munich, Germany*, 2004.

[14] A. Lécuyer, S. Cuquillart, and P. Coiffet, “Simulating haptic information with haptic illusions in virtual environments,” DTIC Document, 2001.

[15] A. Lécuyer, “Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback,” *Presence Teleoperators Virtual Environ.*, vol. 18, no. 1, pp. 39–53, 2009.

[16] F. Argelaguet, D. A. G. Jáuregui, M. Marchal, and A. Lécuyer, “A novel approach for pseudo-haptic textures based on curvature information,” in *Haptics: Perception, Devices, Mobility, and Communication*, Springer, 2012, pp. 1–12.

[17] A. Lécuyer, J.-M. Burkhardt, and L. Etienne, “Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures,” in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2004, pp. 239–246.

[18] L. Dominjon, A. Lécuyer, J.-M. Burkhardt, P. Richard, and S. Richir, “Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments,” in *Virtual Reality, 2005. Proceedings. VR 2005. IEEE*, 2005, pp. 19–25.

[19] P. Kadleček, P. Kmoch, and J. Křivánek, “Haptic rendering for under-actuated 6/3-DOF haptic devices,” in *Haptics: Neuroscience, Devices, Modeling, and Applications*, Springer, 2014, pp. 63–71.

[20] H. Z. Tan, X. D. Pang, and N. I. Durlach, “Manual resolution of length, force, and compliance,” *Adv. Robot.*, vol. 42, pp. 13–18, 1992.

[21] L. S. Taylor, A. L. Lerner, D. J. Rubens, and K. J. Parker, “A Kelvin-Voight fractional derivative model for viscoelastic characterization of liver tissue,” in *ASME 2002 International Mechanical Engineering Congress and Exposition*, 2002, pp. 447–448.

[22] H. Z. Tan, N. I. Durlach, G. L. Beauregard, and M. A. Srinivasan, “Manual discrimination of compliance using active pinch grasp: The roles of force and work cues,” *Percept. Psychophys.*, vol. 57, no. 4, pp. 495–510, 1995.

[23] N. Dhruv and F. Tendick, “Frequency dependence of compliance contrast detection,” *Proccedings ASME Dyn. Syst. Control Div.*, 2000.

[24] L. Nicholson, R. Adams, and C. Maher, “Reliability of a discrimination measure for judgements of non-biological stiffness,” *Man. Ther.*, vol. 2, no. 3, pp. 150–156, 1997.

[25] Gös. Ekman, “Weber’s law and related functions,” *J. Psychol.*, vol. 47, no. 2, pp. 343–352, 1959.

[26] G. A. Gescheider, *Psychophysics: the fundamentals*. Psychology Press, 2013.

[27] S. S. Stevens, *Psychophysics: Introduction to its perceptual, neural, and social prospects*. Transaction Publishers, 1975.

[28] M. Li, H. Liu, J. Li, L. D. Seneviratne, and K. Althoefer, “Tissue stiffness simulation and abnormality localization using pseudo-haptic feedback,” in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, 2012, pp. 5359–5364.

[29] D. A. Gomez Jauregui, F. Argelaguet, A.-H. Olivier, M. Marchal, F. Multon, and A. Lecuyer, “Toward‘ Pseudo-Haptic Avatars’: Modifying the Visual Animation of Self-Avatar Can Simulate the Perception of Weight Lifting,” *Vis. Comput. Graph. IEEE Trans. On*, vol. 20, no. 4, pp. 654–661, 2014.

[30] “Multi-Fingered Palpation using Pseudo-Haptic Feedback.” [Online]. Available: http://www.academia.edu/7689147/Multi-Fingered_Palpation_using_Pseudo-Haptic_Feedback. [Accessed: 19-Nov-2014].