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# Difference of Perceiving Object Softness during Palpation through Single-Node and Multi-Node Contacts

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*Abstract*— **Virtual Reality (VR) simulators can offer alternatives for training procedures in the medical field. Most current VR simulators consider single-node contact for interacting with an object to convey displacement and force on a discrete mesh. However, a single-node contact does not closely simulate palpation, which requires a surface made of a multi-node contact to touch a soft object. Thus, we hypothesize that the softness of a deformable object (such as a virtual breast phantom) palpated through a single-node contact would be perceived differently from that of the same phantom palpated through a multi-node contact with various force arrays. We conducted a study to investigate this hypothesis. Using a co-located VR setup that aligns visual and haptic stimuli onto a spatial location, we tested 15 human participants under conditions of both visual and haptic stimuli available and only visual (or haptic) stimulus available. In a trial, each participant palpated and discriminated two virtual breast phantoms of same softness through different contacts with varying force arrays. The results of this study revealed that virtual breast phantoms palpated through a single-node contact were constantly perceived harder than their counterparts palpated through a multi-node contact with varying force arrays, when visual stimuli were available. These results imply a constraint for developing a VR system of training palpation.**

## I. INTRODUCTION

Real-time virtual reality (VR) simulators could offer alternatives for teaching medical procedures. Using force applied through fingers to assess the health of soft tissues, palpation is a procedure difficult to master. The current technique of training palpation uses phantoms made of hard and soft silicone materials, mimicking the physical behavior of an actual breast. This training technique has been found to be not very effective due to the difficulty in describing touch feeling and the lack of objective assessment [1]. Offering automated recording and force feedback, a VR simulator can be beneficial for training palpation.

Although VR simulators can address some drawbacks present in the current training systems, the key factor of such simulators is to provide a close replication of the real procedure being simulated. Due to the limitation of current hardware, most researchers use a stylus-style haptic device rendering force at a spatial location (single-node contact). Consequently, most current VR simulators consider a single-node contact to convey displacement and force on a discrete mesh of an object [2, 3]. For example, Gurari *et al.* studied softness discrimination using a custom-made haptic device [2]. Sedef *et al.* created a viscoelastic model of a liver running in real time [3]. They were able to interact with the model using a PHANToM haptic device simulating a single-node contact. Unfortunately, the single-node contact diverges from the real procedure of palpation that requires a whole section of the finger (contact area) to touch a soft object for forming a multi-node contact. Conversely, a multi-node contact has the advantage to solve this divergence by allowing the application of force on the nodes within the area contacted by the fingers. Consequently, the multi-node contact could improve the user experience during palpation.

Although VR training systems could gain from a multi-node contact, its usage appears to be seldom in conjunction with a PHANToM haptic device. Nevertheless, we found a few studies using multi-node contact. These studies can be grouped into two categories. One category contains studies using a single-node contact at two to more locations. For instance, Kuroda *et al.* used a glove-style force feedback device to simulate the manipulation of organs in an open surgery [4]. Each finger of this device was represented by a single-node contact. Another category holds studies using multi-node contact forming a contact surface. Indeed, one study used a Signorini contact model, a common paradigm used in the mechanics of contact [5]. Although the Signorini contact model yields a good agreement with its real counterpart, it appears to be too slow for real-time computation of force feedback. Manousopoulos *et al.* studied the pinch of fabrics using one and two fingers [6]. The size of the fingertips was taken into account to compute the displacement of the fabrics in response of applied forces.

Besides these studies on the usage of single-node and multi-node contacts, we were unable to find reports on how such contacts affect subjective perception of object softness in the context of training palpation. During training, trainees learn to apply various forces through the tip of one or two fingers to assess the softness of organs/tissues. In a VR training system, single-node and multi-node contacts might not result in the perception of force feedback from a virtual breast phantom, when a user manipulates a stylus-style haptic device rendering one resultant force feedback to the user's hand (such as a PHANToM device). However, the virtual phantom could still exhibit different visual displacements when palpated via a single-node contact, from those when palpated through a multi-node contact with various force arrays. That is, the difference of visual displacements might affect how the user perceives the softness of a virtual deformable object (e.g., a virtual breast phantom) [7]. Thus, we hypothesize that the softness of a virtual breast phantom palpated through a single-node contact would be perceived differently from that of the same phantom palpated through a multi-node contact with various force arrays, when the deformation of the breast phantom is visible as visual stimuli.

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We undertook a within-subject-design study to verify this hypothesis. Using a virtual breast phantom governed by a real-time viscoelastic model [8], we conducted the study under three palpation scenarios: (1) passive palpation via a robotic arm without rendering force feedback (no haptic stimuli); (2) hidden palpation under obstacles blocking visual stimuli; and (3) active palpation with both visual and haptic stimuli. The results of our study revealed that human participants did not perceive similar level of softness during palpation under single-node and multi-node contacts, when visual stimuli were available.

## II. METHOD

### A. Participants

A total of 15 participants (9 males and 6 females, aged between 20 and 30 years old) participated in our study. With a stereo acuity at least 40" of arc as determined by the Randot Stereotest (Stereo Optical, USA), all participants had normal or corrected-to-normal vision. As verified through a modified version of the Edinburgh handedness inventory [9], they all were strongly right handed. The participants were graduate students at the University of Calgary and were naïve to the purpose of the study. The study followed an ethics clearance approved according to the Canadian Tri-council Ethics Guidelines.

### B. Apparatus

For the study, we used a co-located VR apparatus that aligns visual and haptic stimuli onto a spatial location. In a previous study, we discovered that this particular apparatus had many advantages over other alignments between visual and haptic stimuli [10]. As illustrated in Fig. 1(a), a first-surface mirror was placed horizontally between a stereoscopic monitor and a haptic device. The space between the mirror and monitor was 43 cm. Under the mirror, a haptic device (PHANToM 1.5/6DOF) was placed at the exact location where its reference point was aligned with the visual stimuli reflected by the mirror. Sitting in front of the apparatus, the participant employed his/her right hand to operate the haptic device without viewing the hand. On the mirror, the participant was able to see a virtual index finger moving according to the reference point of the haptic device. A fixed forehead rest was placed at the same height as the monitor to constrain the location and orientation of the participant's head. This warranted that each participant was able to feel and see stimuli in a relatively consistent way.

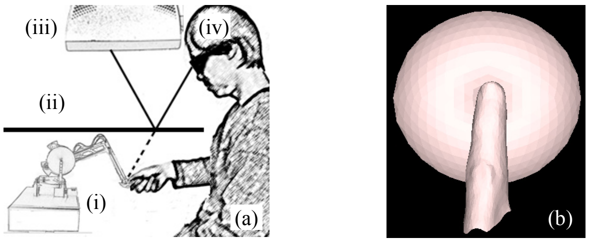

Figure 1. Apparatus and visual stimuli. (a) Co-located apparatus: (i) haptic device; (ii) mirror; (iii) 3D stereoscopic monitor; and (iv) shutter glasses. (b) Visual stimuli with one finger as a cursor on the top of the virtual phantom.

### C. Stimuli

Together, visual and haptic stimuli simulated a task of palpating and discriminating object softness. Two homogenous virtual breast phantoms of the same softness and identical size (hemisphere with a diameter of 8 cm and 338 nodes meshed on the hemispherical surface) were presented one after another to the participant. Both phantoms were seen from the top as shown in Fig. 1(b). The deformation of the phantom was governed by a real-time viscoelastic model with material properties of an actual breast phantom, as described in our earlier work [8]. To interact with each phantom, the participant moved a cursor shaped as an index finger through the haptic device. The distal segment of the finger (fingertip) has a contact area of 2 cm x 2.84 cm to cover 23 meshed nodes of the phantom. The participant could only apply force via the fingertip on the top of each virtual phantom. In each trial, a pair of different force arrays was randomly assigned to these virtual phantoms. Six pairs of different force arrays were formed by the following four arrays:

1. Single-node contact (Force Array 1): one node at the fingertip's center conveyed force to the phantom.
2. Homogenous multi-node contact (Force Array 2): all nodes on the fingertip conveyed the same force.
3. Centered 2D Gaussian multi-node contact (Force Array 3): each node on the fingertip conveyed force following a 2D Gaussian distribution with its peak located at the center of the fingertip.
4. Off centered 2D Gaussian multi-node contact (Force Array 4): each node on the fingertip conveyed force computed by a 2D Gaussian distribution with its peak located at the distal end of the fingertip.

All force arrays had a maximum resultant of force at 3.5 N – the maximum sustainable force of the PHANToM 1.5/6DOF haptic device. To simulate a breast phantom with a consistent level of softness among these force arrays, we normalized force feedback derived from the real-time viscoelastic model of the phantom by the number of nodes in contact. Under single-node or multi-node contacts, an similar resultant of force (less than 5% difference) thus was fed back from the phantom to yield comparable vertical movement of the reference point of the haptic device. Nevertheless, the visual displacement of all meshed nodes on the virtual phantom generated various deformations under these force arrays, governed by the real-time viscoelastic model. In C++ programming language, we used OpenGL and OpenHaptics to develop both visual and haptic stimuli.

### C. Procedure

Each participant was instructed to handle the stylus of the haptic device in close replication of using the index finger in a palpation task: with the index finger straight along the elongated axis of the stylus. Each participant was told that a safety threshold of force was set to protect the haptic device. In each trial, the participant saw and palpated two phantoms of different colors (but same luminance) one after another; and then selected the harder one between the two presented. The study used the paradigm of two Alternative-Forced-Choice normally found in psychophysics studies. Every participant took part the following testing conditions:

- Passive palpation (Vonly): No force feedback was available. The participant could only see the phantom deformation while palpating it through the haptic device. This scenario mimics palpation under a robotic arm without force feedback.
- Hidden palpation (Honly): No visual stimulus was displayed to the participant when palpating the phantom. The participant could only feel force feedback during palpation. This scenario simulates palpation under obstacles blocking vision.
- Active palpation (V+H): Both visual and haptic stimuli were presented to the participant. He/she could view the phantom to deform and feel force feedback during palpation. This is a common scenario of palpation in practice.

Each testing condition had a practice session of 10 trials and a testing session of 30 trials (6 catching trials for the comparisons of force arrays and 24 testing trials: 6 comparisons x 4 repetitions). The practice session aimed at accustoming the participant with each testing condition and the palpation task. The trials in this session randomly derived from those in the testing session to cover both catching and testing trials. A catching trial consisted of two phantoms palpated through two different force arrays but with different levels of softness apart of 50% (much larger than the Just-Noticeable-Difference of 15% [11]). In each testing trial, both phantoms possessed the same softness but were palpated through two different force arrays.

The order of all conditions and trials was randomized and counterbalanced among all participants. A practice and testing session lasted about 10 and 20 minutes, respectively, resulting in a total of roughly 1.5 hours for each participant.

### *E. Data Recording and Analysis*

Subjective selection of a harder one among the two virtual phantoms was recorded during each trial. For each participant, we examined his/her selection of all catching trials to ensure that no difficulty arose in discriminating the softness of two phantoms. Then, we discarded the recordings of all catching trials and processed those from all testing trials by applying the statistical method of within-subject-design ANOVA (analysis of variances). ANOVA indicates a statistically significant difference among datasets by using $F$- and $p$-values. Representing an experimental error, the $F$-value is given by the ratio of the variance of each dataset and the variance of all datasets. The $p$-value represents the probability that chance is the main factor for explaining the variation among all datasets.

## III. RESULTS

To investigate the effect of testing conditions and array comparisons on subjective perception of object softness, results from a two-way ANOVA (force array comparisons × testing conditions) revealed that subjective perception of object softness had significant effect among the three testing conditions [$F(2, 14) = 3.683$, $p < 0.05$] and six comparisons of force arrays [$F(5, 14) = 6.694$, $p < 0.001$]. Furthermore, this analysis indicated that there was a significant interaction between testing conditions and force array comparisons [$F(10, 14) = 2.381$, $p < 0.05$]. Fig. 2 depicts the general trends associated with these findings of significance. The horizontal axis of this figure labels tested comparisons of force arrays. For example, the label "2 vs. 4" means that the Force Array 2 (Force Array α) was compared to Force Array 4 (Force Array β). The vertical axis indicates the proportion of the virtual phantom palpated through the " Force Array α" selected as harder in each pair of comparison. Under the condition of passive palpation (Vonly), Fig. 2 shows that the phantom palpated through Force Array 1 (single-node contact) was perceived harder than its counterpart palpated through Force Arrays 2, 3, and 4 (multi-node contact) in more than 75% of the trials.

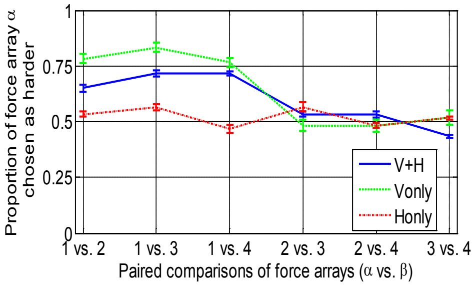

Figure 2. Subjective perception of object softness (α vs. β). Error bars represent standard errors.

Further analyses were performed to investigate what pairs of force array comparisons under each testing condition play a role in the above observations. Table I indicates the outcomes of a one-way ANOVA (force array comparisons, the 2nd column) for each available testing condition. The 3rd and 4th columns of this table present the results of pairwise contrast using a Bonferroni correction under each available testing condition. The Bonferroni correction serves to offset the error introduced when performing multiple computations. Under the condition of passive palpation (Vonly), the phantom palpated through Force Array 1 was chosen as significantly harder than its counterpart palpated through multi-node contacts (Force Arrays 2, 3 and 4), as depicted in Fig. 2 and Table I. Furthermore, there was no significant difference of perceiving object softness between any two multi-node contacts (Force Arrays 2, 3 and 4). The condition of active palpation (V+H) follows the similar trend; but differs only between single-node contact (Force Array 1) and homogenous multi-node contact (Force Array 2). This difference might reflect a mild influence of the available haptic information. However, the perception of object softness was not influenced by the force feedback from the phantom under the condition of hidden palpation (Honly). Among all single-node and multi-node contacts, the participants did not differentiate significantly the softness of both virtual phantoms [$F(5, 14)=0.719$, $p>0.05$].

One-way ANOVA among testing conditions indicated that the comparisons of "1 vs. 2", "1 vs. 3" and "1 vs. 4" had significant difference in perceiving object softness, as illustrated in Table II. A pairwise contrast with the Bonferroni correction shows that only the pair of conditions of passive palpation (Vonly) and hidden palpation (Honly) produces this significance. No significant difference was found among other testing conditions. This reinforces the

TABLE I
RESULTS OF ANOVA AND PAIRWISE CONTRAST FOR THE EFFECT OF FORCE ARRAYS ON SUBJECTIVE PERCEPTION OF OBJECT SOFTNESS

| | **One-way ANOVA $F(5,14)$** | **Pairwise Contrast (Bonferroni)** | |
|---|---|---|---|
| Vonly | $F=7.506$, $p<0.01$ | 1 vs. 2 <-> 2 vs. 3 | $p<0.01$ |
| | | 1 vs. 2 <-> 2 vs. 4 | $p<0.05$ |
| | | 1 vs. 2 <-> 3 vs. 4 | $p<0.05$ |
| | | 1 vs. 3 <-> 2 vs. 3 | $p<0.01$ |
| | | 1 vs. 3 <-> 2 vs. 4 | $p<0.01$ |
| | | 1 vs. 3 <-> 3 vs. 4 | $p<0.01$ |
| | | 1 vs. 4 <-> 2 vs. 3 | $p<0.01$ |
| | | 1 vs. 4 <-> 2 vs. 4 | $p<0.01$ |
| | | 1 vs. 4 <-> 3 vs. 4 | $p<0.05$ |
| V+H | $F=4.709$, $p<0.01$ | 1 vs. 2 <-> 3 vs. 4 | $p<0.05$ |
| | | 1 vs. 3 <-> 2 vs. 3 | $p<0.05$ |
| | | 1 vs. 3 <-> 2 vs. 4 | $p<0.05$ |
| | | 1 vs. 3 <-> 3 vs. 4 | $p<0.01$ |
| | | 1 vs. 4 <-> 2 vs. 3 | $p<0.05$ |
| | | 1 vs. 4 <-> 2 vs. 4 | $p<0.05$ |
| | | 1 vs. 4 <-> 3 vs. 4 | $p<0.01$ |
| Honly | $F=0.719$, $p>0.05$ | - | - |

finding that object softness under a single-node contact is perceived differently from under multi-node contacts, when visual stimuli were available.

## IV. DISCUSSION

The above observations indicate that a virtual phantom palpated through a single-node contact was constantly perceived harder than its counterpart palpated via a multi-node contact with varying force arrays. This observation is true under both conditions of passive palpation (Vonly) and active palpation (V+H). As a limitation, the PHANToM haptic device cannot render an array of force feedback for a multi-node contact (surface of a fingertip). Thus, a similar resultant of force feedback was used among all force arrays. This limitation might cause humans to perceive no difference among the various force arrays under the condition of hidden palpation (Honly). This observation agrees with that derived from a study on the role of feeling force in perceiving object size [12]. The study reported that humans perceive differently object size when the fingertips were anesthetised. The absence of feeling precise force might explain the lack of different perception of object softness among force arrays 2, 3 and 4, when palpating through a multi-node contact.

Together, our observations confirm the hypothesis of this current study and yield the dominance of visual information in palpation. This dominance agrees with findings from investigating the role of vision in integrating multiple senses. For example, Srinivasan *et al.* found that humans rely more on visual information to discriminate object softness than on haptic information [13]. Derived from these observations, one consideration is for developing a VR system of training palpation. The exclusion of a single-node contact would be a constraint in such a development to match intrinsic characteristics of palpation using the fingers. Another consideration falls into the field of robot-assisted surgical systems. Because most of such systems render currently no force feedback as passive palpation, a surgeon (or trainee) relies only on visual stimuli from an operational site. Thus, the difference of perceiving object softness between single-node and multi-node contacts could influence surgical/training outcomes.

TABLE II
RESULTS OF ANOVA AND PAIRWISE CONTRAST FOR THE EFFECT OF TESTING CONDITIONS ON SUBJECTIVE PERCEPTION OF OBJECT SOFTNESS

| | **One-way ANOVA $F(2,14)$** | **Pairwise Contrast (Bonferroni)** | |
|---|---|---|---|
| 1 vs. 2 | $F=4.561$, $p<0.05$ | Vonly <->Honly | $p<0.05$ |
| 1 vs. 3 | $F=5.437$, $p<0.01$ | Vonly <->Honly | $p<0.05$ |
| 1 vs. 4 | $F=5.271$, $p<0.05$ | Vonly <->Honly | $p<0.05$ |
| 2 vs. 3 | $F=1.123$, $p>0.05$ | - | - |
| 2 vs. 4 | $F=0.225$, $p>0.05$ | - | - |
| 3 vs. 4 | $F=0.579$, $p>0.05$ | - | - |

## V. CONCLUSION

This study revealed that a single-node contact yielded harder perception of object softness than a multi-node contact, when visual information was available. Future work is to investigates the levels of perceptual difference under both single-node and multi-node contacts.

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