Investigating Passive Presentation Paradigms to Approximate Active Haptic Palpation

Pijuan Yu[1], Luke C. Batteas[2], Thomas Ferris[3], M. Cynthia Hipwell[1], Francis Quek[4], and Rebecca F. Friesen[1]

***Abstract*—Active, exploratory touch supports human perception of a broad set of invisible physical surface properties. When traditionally hands-on tasks, such as medical palpation of soft tissue, are translated to virtual settings, haptic perception is throttled by technological limitations, and much of the richness of active exploration can be lost. The current research seeks to restore some of this richness with advanced methods of passively conveying haptic data alongside synchronized visual feeds. A robotic platform presented haptic stimulation modeled after the relative motion between a hypothetical physician's hands and artificial tissue samples during palpation. Performance in discriminating the sizes of hidden "tumors" in these samples was compared across display conditions which included haptic feedback and either: 1) synchronized video of the participant's hand, recorded during active exploration; 2) synchronized video of another person's hand; 3) no accompanying video. The addition of visual feedback did not improve task performance, which was similar whether receiving relative motion recorded from one's own hand or someone else's. While future research should explore additional strategies to improve task performance, this initial attempt to translate active haptic sensations to passive presentations indicates that visuo-haptic feedback can induce reliable haptic perceptions of motion in a stationary passive hand.**

***Index Terms*—Multi-modal Systems, Haptic Display, Passive Perception, Palpation**

I. Introduction

PALPATION is a complex skill performed by health care professionals that is a fundamental part of modern medical examination [1]. Palpation exams typically involve clinicians manually probing patient body locations, such as the head, neck, or abdomen, with one or both hands. Guided by expert knowledge and clinical reasoning, practitioners actively explore the patient's anatomy, collecting haptic cues that contribute to medical assessment and decision making. This activity requires extensive experiential training to master.

The active, manual nature of medical palpation presents several issues. Firstly, it hampers the use of palpation in contexts where the patient and caregiver are not co-located, such as in telehealth settings, thus limiting the benefits that such exams otherwise offer, particularly to rural or home-bound patients [2]. Secondly, it prevents medical students from easily experiencing the haptic sensations produced by their instructor's expert palpation; instead, traditional palpation training relies on a drawn-out process that combines verbal descriptions of haptic sensations, live demonstrations, and student practice complemented by individualized feedback [3].

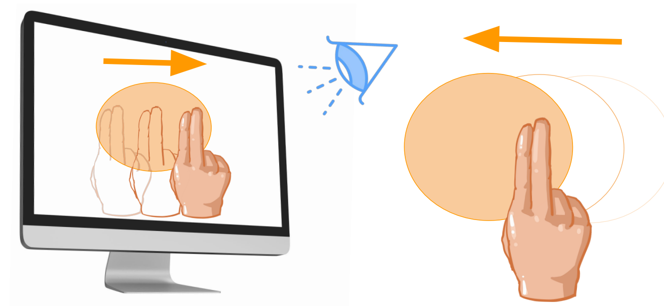

Fig. 1. **Passive touch method.** Passive presentation of an active task: a passive user observes video of active hand motion while a 2D robotic platform recreates the relative motion between the hand and object.

Telehaptic systems – which can capture, transmit, and replay haptic stimulation – offer potential means to address these issues facing medical palpation as well as any touch-based assessment or teaching task. These systems can be configured to record tactile and kinesthetic sensations of a hands-on task, then apply the recorded sensations to the stationary hands of any distant collaborator, supervisor, or student. Such a paradigm requires as-yet undeveloped technology that must accurately capture all necessary haptic components of the touch interaction. More immediately, it is not known whether people can adequately interpret presented haptic sensations that are not evoked by their own active movements.

Toward the development of a telehaptic palpation system, the goal of our study is to explore the fundamental ability to interpret touch sensations from traditionally active manual tasks when applied to their passive (i.e. stationary) hands. To what degree does haptic perception decrease under passive presentation conditions, and what can be done to mitigate any reductions in perception? To address these questions, we applied actively induced sensations to a passive hand by moving silicone phantoms (fake tissue samples) under the passive hand. Some presentation conditions included synchronized visual feedback that showed another person's hand performing the active task; see Fig. 1. Hand and finger movement behaviors, performance (i.e., accuracy of interpretation of the haptic cues), and subjective experience measures (such as feelings of embodiment) were recorded and compared across display conditions. The results generally show the best performance for active manual interaction, but illustrate initial successes

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in our developed system for supporting passive touch and uncovering new challenges to be addressed in future research.

While the broader research questions are applicable to haptic perception under passive conditions in a wide variety of domains, we chose to center our study and task around medical palpation, given the potential benefits to supporting telehealth and medical training/education.

A. Haptic Feedback for Palpation

In recent decades, considerable research has been directed towards providing haptic palpation feedback to medical practitioners and students. When interacting with real patients, options primarily consist of restoring haptic sensations to a remote doctor performing active teleoperated palpation [4]–[6]. Here, a sensorized tool touches the patient and resultant recorded forces are transmitted to the doctor and applied via an actuated tool or wearable glove. Haptic feedback for medical palpation training can be generated via simulations. These can consist of: (i) physical simulated tissue, often rubber, providing anatomical likeness and some degree of haptic feedback [7]–[10]; (ii) virtual reality (VR), employing pure virtual simulators, incorporating a head-mounted display (HMD) coupled with haptic devices like a pneumatic haptic glove [11] or ultrasound system [12]; and (iii) mixed reality (MR), a hybrid system that amalgamates haptic devices and virtual media to provide comprehensive feedback [13]–[16]. This research into tele-operated and simulated touch demonstrates a strong need for alternatives to hands-on palpation. All of these solutions, however, continue to rely on active touch interactions. This prevents doctors from experiencing exams performed asynchronously, or multiple doctors and students experiencing the same palpation exam. These scenarios could be facilitated by applying previously-gathered sensations to a practicioner's passive hand, presuming they could interpret the sensations in that context.

B. Passive Haptic Perception

A passive paradigm for palpation training hinges on a key question: how do people perceive and interpret actively collected haptic sensations when passively applied to another hand? Since Gibson's 1962 article comparing active touch (touching) and passive touch (being touched) in the perception of shape, passive perception has attracted significant research interest [17]. Previous research has demonstrated that human perception of surface roughness remains intact both in active and passive touch [18]–[20]. Beyond that, studies also suggest that passive touch is better than active touch for recognizing local shapes stimulated by vertical displacements of the finger [21]. While the aforementioned works repeatedly demonstrate that human perception remains unchanged in the absence of active movement, these findings should be further challenged: these experiments do not replicate the finger's natural movement while performing active touch, a limitation that fails to mimic the natural exploratory process of the finger during active touch.

C. Passive Visio-haptic Perception

In addition to haptic feedback, considerations concerning visual feedback must also be addressed. Although the diagnostic accuracy of palpation primarily depends on haptic cues rather than visual or auditory ones, conventional palpation instruction requires practitioners to concentrate on both the examination area and the patient's facial expressions [22]. In a passive touch context, however, providing synchronized visio-haptic feedback on the palpated region proves challenging due to limitations of video viewing angles and unpredictable hand movement. Furthermore, receiving sensory input from multiple channels may sometimes result in sensory confusion, as evidenced by studies showing superior performance by the blind in certain touch-based tasks [23]. Given that palpation relies more on haptic than visual feedback, there is a need to ascertain whether synchronous video would enhance tactile acuity or distract practitioners, consequently affecting diagnostic accuracy.

D. Enhancing Passive Touch via Illusions

A potential approach to address the multifaceted challenges within our passive visuo-haptic feedback system is the application of the rubber hand illusion (RHI) theory, specifically to induce related illusions of agency and ownership. Traditionally, this psychological phenomenon allows individuals to perceive an artificial hand as their own through the reception of passive haptic feedback from a concealed static hand and visual feedback of analogous physical contact with a visible artificial rubber/virtual hand [24]. Such an illusion fosters a more immersive experience within the palpation simulation environment, potentially mitigating potential distractions.

Recent methodologies for inducing RHI include (i) tactile stimulation, applying synchronous tactile stimuli to both real and artificial hands [24]–[28]; (ii) passive movements, involving the synchronous experimenter-induced movements of both hands [27]–[29]; and (iii) active movements, entailing the synchronous, participant-induced movements of both the real and artificial hand [26]–[32]. Active participant movement further provides opportunities to examine sensations of agency, which can significantly affect the synchrony-induced ownership illusion [26], [33]. Regardless of methodology, most extant moving rubber hand illusions demand the synchronous movements of the participant's own hand and the artificial hand [34]. However, no research we know of has explored whether such an illusion can be triggered in the passive touch scenario previously described, wherein tactile stimuli are applied to a subject's static hand concurrently with a video of a moving virtual hand executing a palpation procedure.

In addition to the rubber hand illusion, consideration must be given to the kinesthetic illusion (KI) phenomenon, which manifests as an illusion of self-body movement without actual physical motion. This effect is pertinent since the passive touch mode involves a static hand coupled with video of a moving hand. Historically, kinesthetic illusions have been induced through methods such as tendon vibration [35], touch [36], or visual cues [37], [38]. However, as the conventional induction methods for kinesthetic illusions—such as the mirror illusion paradigm—are not entirely congruent with the passive touch situation, new understandings must be developed. Uncertainty still exists concerning whether similar feelings can be induced if the viewed moving hand is perceived to belong to another person.

E. Platform for Rendering Passive Palpation Sensations

In order to explore enhancements to passive interpretation of active haptic tasks such as palpation, we developed a 2D robotic platform which can record hand movement during active tasks, then render comparable sensations to a passive hand via continuous synchronized visual and haptic feedback. Cutaneous and some kinesthetic feedback arises from the robotic platform moving stimuli with respect to the stationary hand, while additional information regarding hand location is provided by the visual playback of the original active movement.

We conducted a psychophysical study to observe impacts of different passive presentation techniques on size discrimination of tissue-embedded lumps. Our goal was to observe contributions of different visual and playback options to enhancing passive perception; therefore, we limited our experiment to a single task of size discrimination. Future work examining perception of other common palpation features such as stiffness [39], [40] will likely require implementation of force control in the robotic platform. Participants were asked to distinguish different lump sizes in anatomically-inspired tissue phantoms and report their confidence in making such assessments. This task was performed both actively and under several different passive conditions, and presence of rubber hand illusion was measured for the passive visuo-haptic conditions. In the following section we detail construction and operation of our 2D robotic platform, followed by a discussion of our psychophysical study.

II. Materials and Methods

Our experimental platform for rendering visuo-haptic feedback consists of three parts: a rubber tissue phantom constructed to mimic human tissue, a 2D platform to move the phantom with respect to a passive hand, and a monitor to provide synchronous visual feedback of an active hand moving with respect to a stationary phantom. In this section, we detail our design considerations and characterize device behavior.

A. Rubber Tissue Phantom

In order to supply a range of differentiable palpation sensations, we designed a series of soft tissue phantoms to closely mimic palpated features in real patients. Specifically, we focused on phantoms for neck palpation examinations to detect the thyroid cancer. In order to ensure realistic feeling phantoms, we consulted with physicians from Houston Methodist Hospital (see acknowledgements), including an Ear Nose and Throat specialist, during design and assessment stages of phantom construction.

Existing phantoms often adopt simplistic shapes such as cuboids [41]–[45] or truncated cones [5], [46] and are embedded with lumps, usually made from silicone rubber to mimic human skin tissue. However, these phantoms do not adequately replicate the realistic texture of nodes or glands found in the neck's soft tissue. Common materials for these lumps include plastic materials such as Delrin [42] and resin [45], which have elastic moduli significantly higher than that of human thyroid cancer tissue—approximately 3.1 GPa and 2.8 GPa [45], respectively, compared to only 45 kPa for thyroid cancer tissue [40].

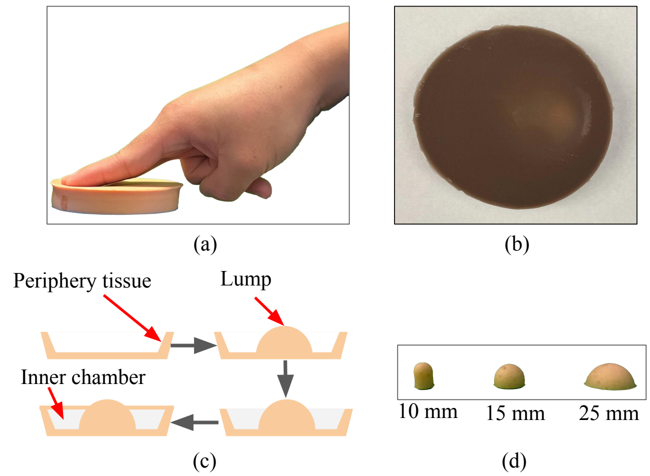

Fig. 2. **Soft silicone rubber tissue phantom.** (a) Side view. (b) Top view. (c) Phantom making procedure. (d) three different sizes of lumps.

In contrast, our phantoms, depicted in Figure 2, are segmented into three parts: (i) the outer layer represents the skin surface, constructed from Ecoflex 00-10 with an elastic modulus of 37 kPa, mimicking the softness of actual skin [47]; (ii) a central cavity filled with mixed viscous liquid (Elmer's Clear Glue, Elmer's Magical Liquid Slime Activator) to emulate soft tissue and lubrication between skin and underlying muscle; (iii) a silicone lump, also of Ecoflex 00-10 material and available in three sizes of 10, 15, and 25 mm in diameter to reflect the size range of thyroid cancer [48].

Regardless of diameter, each lump maintains a uniform height of 11 mm. The lumps remain subtly detectable to the touch as slight protrusions on the phantom's surface. They are colored to match the surrounding tissue, making them visually indiscernible, thereby necessitating hands-on interaction for size differentiation.

B. Moving Platform

The experimental platform that moves the tissue phantom under a passive hand is shown in Fig. 3. We used an XYZ translation stage (FSL40, Fuyu Technology Co., China) composed of three Nema 17 stepper motors (BE069-3, Befenybay) that provide a resolution of 0.011625 mm per step. To address the challenge of motor vibration, the microstepping method was applied, optimizing resolution and dampening vibration noise through the utilization of three stepper motor drivers (DM542T, OMC Corporation Limited, China). These drivers interface with an Arduino Due microcontroller using the AccelStepper package, and the Due communicates with the host computer via Pyserial. The vertical linear stage connects

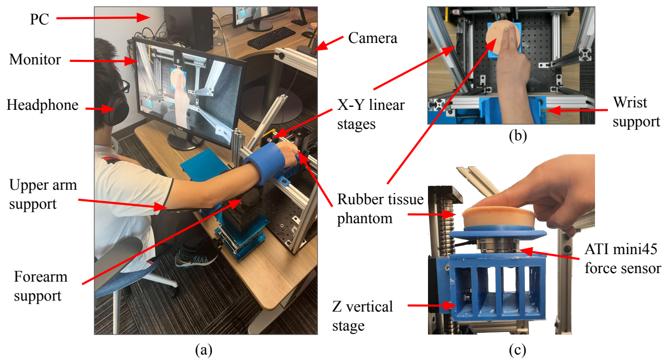

Fig. 3. **Experiment setup.** (a) System overview. (b) Top view. (c) Side view.

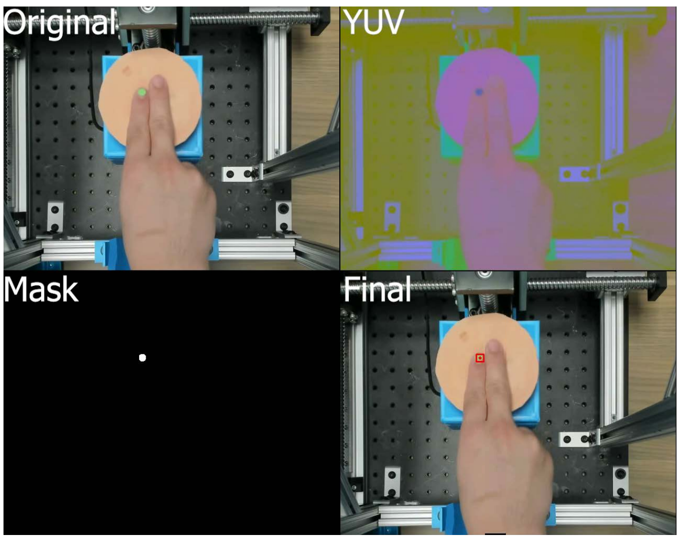

Fig. 4. **Finger tracking procedure.** The top-left image represents the original RGB format, while the top-right image illustrates the transformed YUV format. The bottom-left image depicts the mask image, exclusively encompassing the contour of the green sticker. The bottom-right image is designated as the tracked image, containing a red rectangle; the center of this rectangle symbolizes the precise position of the finger.

to a support structure with a rubber damper layer incorporated to mitigate remaining vibrations. An ATI Mini 45 force sensor is integrated at the bottom of the tissue phantom to record the force value.

C. Trajectory Generation

Positioned above the phantom, a 720p RGB camera (Logitech BRIO webcam, Logitech)serves to capture the finger's movement during the active touch procedure. We limited camera capture to 30 fps, which we deemed adequate to capture the characteristics paths such as that in Fig 5(b), in order to minimize system computational demands. In the implementation of hand tracking shown in Fig 4, the RGB camera serves dual functions: (1) documenting an active palpation exam for future visual feedback and (2) tracking a designated green sticker affixed to the fingernail, thereby capturing finger position during said exam. Utilizing the YUV colorspace tracking algorithm, aided by OpenCV, it surpasses the noise-sensitive RGB color model in stability under varied lighting conditions.

Transitioning from 2D pixel coordinates to 3D world coordinates presents a significant challenge, particularly in the absence of stereo camera data and concomitant depth information. However, given the fixed camera's pose relative to the phantom and the nature of the finger's sliding movement, an alternative method was devised. The conversion from 2D pixel coordinates to 2D world coordinates (in millimeters) was undertaken using intrinsic parameters to rectify pixel coordinate distortions and extrinsic parameters to translate the corrected 2D pixel coordinates. This transformation was calibrated through a standardized process involving an 8x8 printed chessboard as a reference object.

Active palpation of tissue phantoms are recorded with 720p video at a rate of 30 frames per second (FPS). Subsequently, this video is transmitted to the computer and decoded using the aforementioned finger tracking methodology to obtain a waypoint array consisting of approximately 900 data points per 30 seconds of video. From these waypoints, an estimated raw trajectory is generated through linear interpolation. This procedure is outlined in Fig 5 (a).

D. Trajectory Smoothing

In order to provide synchronous visuo-haptic feedback for a pre-recorded video, several primary constraints are observed. Firstly, the purpose of this trajectory is to emulate the haptic feedback correlating to the video's movement; the trajectory is thus pre-determined by the video content, though adaptations or smoothing may be necessary to accommodate hardware capabilities. Secondly, to augment efficiency and preclude delays attributed to computer performance, the playback of the video via OpenCV and the execution of the trajectory are separated. Consequently, the smoothed trajectory must be generated and imported into the microcontroller prior to the video's playback. Thus, the number of data points must be constrained due to the local memory limitations of the microcontroller, which might affect real-time performance. Thirdly, even with limited waypoints for smoothed trajectories, the smoothed trajectory must closely align with the original to synchronize with the video movement without noticeable lag. Finally, the duration of the smoothed trajectory must correspond precisely with the video's duration. After extensive testing of various algorithms, a low pass filter (Gaussian filter, sigma = 8) was chosen to smooth this rough trajectory without discernible lag. Fig. 5 (b) - (d) compare the raw trajectory collected from a typical video recording and actual motor trajectory.

E. Visio-haptic Synchronization

Upon importing the smoothed trajectory matrix into the Arduino Due via Pyserial, the subsequent step involves executing this trajectory and concurrently playing back the original video on the monitor (see Fig. 5 (a)). To realize this objective, the Arduino sends a trigger message to the Python loop and initiates the stepper motors when the last data point is received. When the Python loop receives this trigger message, the video

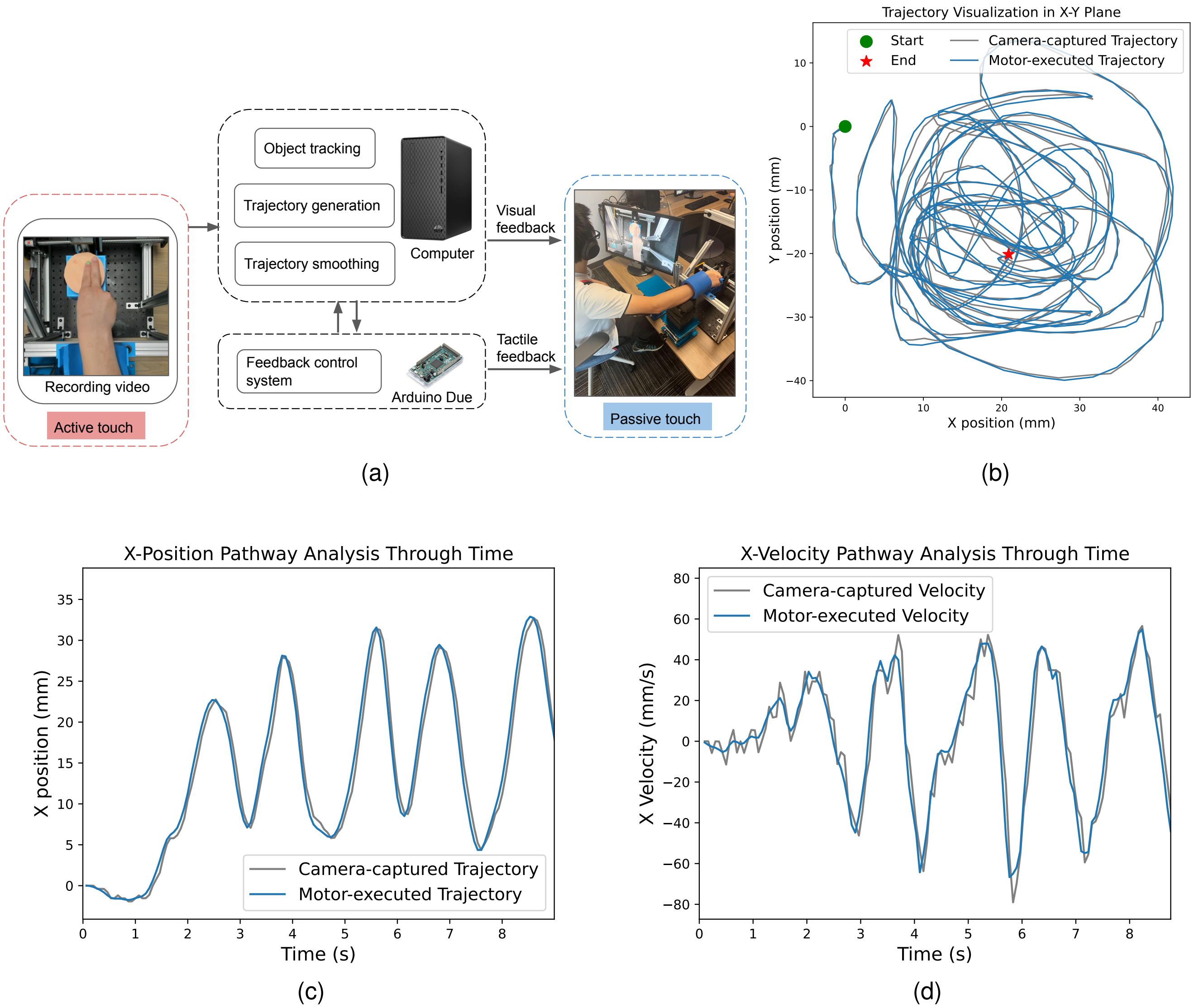

Fig. 5. **Trajectory smoothing and execution** (a) System architecture: Render the visual and tactile sensations from the local "Tutor" in a pre-recorded video to the remote "Practitioner". (b) Trajectory Visualization on a 2D Plane: A green dot denotes the starting point, while a red star indicates the end point. The gray line illustrates the raw trajectory, generated from tracking the green dot. The blue line depicts the actual trajectory derived from the stepper motor encoder, executed by a Feed-forward + Feedback proportional controller. (c) Graph of X Position vs. Time: This is represented over an initial duration of approximately 8 seconds. (d) Graph of X Velocity vs. Time: This is showcased within an initial span of around 8 seconds.

is displayed via OpenCV. Two major challenges emerge in this context. The first challenge pertains to synchronizing the commencement of the video with the stepper motors. The second challenge revolves around ensuring that the duration of the video aligns with the duration of the stepper motor movement. In addressing the first challenge, four timestamps were employed to investigate and quantify the system's delay. A subsequent discovery revealed a consistent delay between two specific timestamps due to Python taking approximately 50 milliseconds to display the first video frame upon receiving the trigger message. A manual 50 milliseconds delay was then integrated into the Arduino loop to synchronize the commencement of the stepper motor with the video.

The second challenge involves aligning the actual movement duration with the smoothed trajectory duration, a discrepancy that might lead to asynchronicity between touch and visual feedback. This misalignment occurs despite the matched duration of the smoothed trajectory and the video. To remedy this problem, a classical feedforward plus feedback speed control system encompassing a proportional controller (Kp = 10) was implemented to manage the trajectory for the time asynchrony issue. Additional timestamps were also used to verify and illustrate the synchronization between the last video frame's appearance and the trajectory's termination in the Arduino loop.

F. Indentation Force characterization

The current iteration of our experimental platform provides 2D position control, not force control, of haptic stimuli.

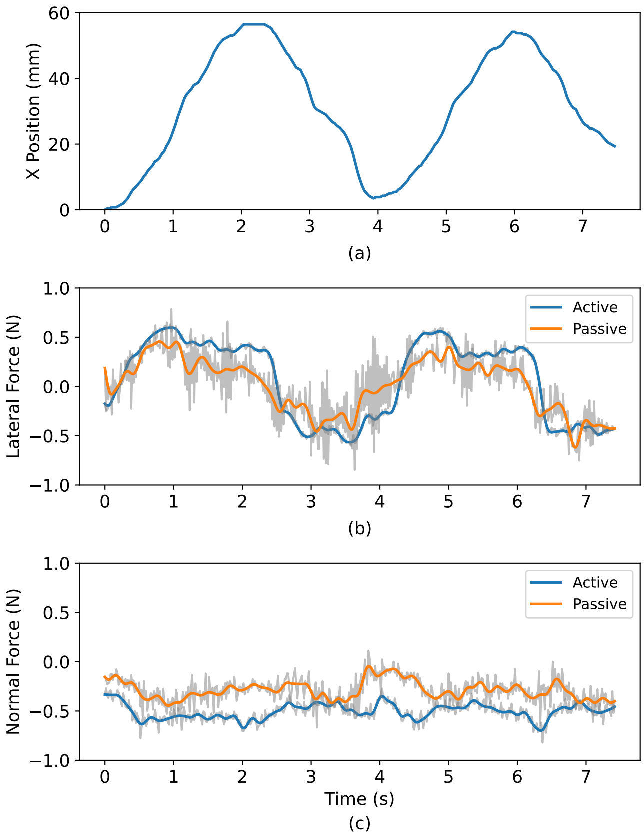

Fig. 6. **Indentation Force characterization.** (a) Trajectory X Over Time: The top graph displays the x-axis position of the lead author's finger as it slides back and forth over a tissue phantom lump. (b) Active vs Passive (Lateral Force Data): The middle graph presents the lateral force values, with the blue line representing active touch and the orange line depicting passive touch recordings. (c) Active vs Passive (Normal Force Data): The bottom graph depicts the normal force values for both active and passive touch.

Therefore, we chose to limit our experiments to size detection instead of characteristics such as stiffness which would be overwhelmingly reliant on force feedback. Recognizing the pivotal role of force in all tactile perception, however, we characterized interaction force for the lead author's finger under both active and passive interaction with a tissue phantom lump. Force data was collected with a 6-axis sensor (ATI Mini45) placed directly under the phantom, sampled at 60 Hz and low pass filtered at 5 Hz to mitigate signal noise. Representative data is shown in Figure 6; variations in force were similar across both conditions. Force was slightly offset to smaller values under the passive condition, likely due to the finger passively resting on top of the stimulus instead of actively pressing down. As the finger slides over an embedded lump, it will gently rise and fall, transmitting haptic information through motion as well as force.

III. Psychophysical Experiment

The objective of this experiment is to investigate whether the diagnostic outcome from a palpation task remains accurate without any active movement. We also explored whether phenomena such as the rubber hand illusion and kinesthetic illusion can be elicited by administering continuous haptic feedback to the subject's static concealed passive hand, concurrently with the display of a synchronously moving virtual hand on the screen.

A total of eighteen participants (11 men and 7 women, aged between 18 and 45) were enlisted for this experiment. All participants possessed a healthy physique and normal sensation, with right-hand dominance. Most participants were engineering students at Texas A&M University, and all lacked prior palpation experience or theoretical knowledge pertaining to general physical examination. This experiment was approved by the Institutional Review Board of Texas A&M University (IRB2022-0798D), and all participants signed the informed consent form prior to participation and received compensation for their involvement.

Our experimental protocol was structured into two distinct sessions. The initial session served as a training phase, designed to familiarize participants with the entire setup. Following this, the second session constituted the formal experimental phase. Detailed descriptions of each phase are provided below.

A. Session 1: Training and Trajectory Capture

The first session was primarily designed to facilitate participants' familiarity with both the rubber tissue phantom and the overall experimental setup. Near the end of this training procedure, we also captured video of active movement trajectories, unique to each participant. This session consisted of three specific tasks detailed below.

Task 1: Participants were presented with three tissue phantoms all at once, each containing lumps of varying sizes, and were required to arrange them from left to right based on size using active touch. This task aimed to confirm the participants' ability to distinguish the three different lump sizes detailed in section II-A.

Task 2: Participants were instructed to place their right hand on the apparatus, equipped with adjustable arm and wrist support. A demonstration of "passive touch," in which they held still while a phantom moved under their hand, was provided to acquaint them with the palpation process, in preparation for the subsequent task.

Task 3: Participants affixed a green sticker to their fingernail and were instructed to keep their hand in a specific two-finger posture, pictured in Fig. 4, for a duration of 30 seconds. Starting from a marked point (a black dot), they actively explored the lump on each rubber tissue phantom. This exploration was recorded as video, with the stipulation that the touch pattern consist solely of sliding touch, excluding tapping or rapid shaking. Three videos were recorded for each participant, to be utilized in the subsequent session.

B. Session 2: Participant Performance Across Conditions

Our experimental session was divided across four condition blocks, in order to observe diagnostic performance of participants under various active and passive touch scenarios detailed in Fig 7. Conditions 1 and 2 were chosen to compare active versus passive touch conditions, both without video feedback. Conditions 2 and 3 compared performance across

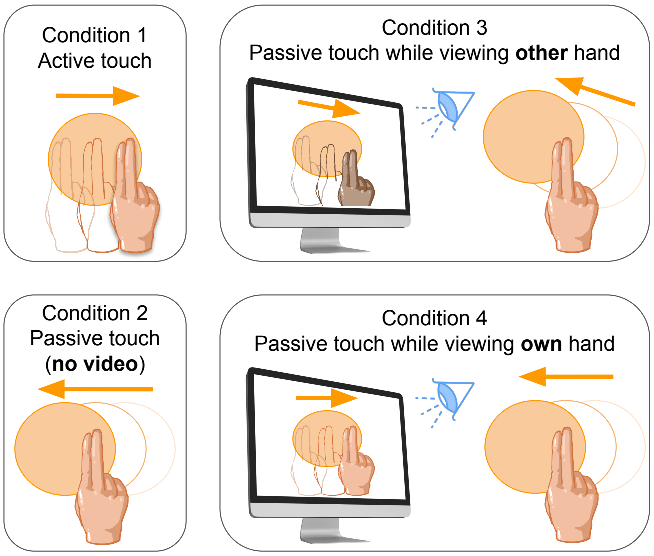

Fig. 7. **Four conditions.** i) Condition 1 Active touch: Participants were instructed to freely explore the hidden tissue phantom. ii) Condition 2 Passive touch without video: Participants kept their hand stationary, allowing the robotic platform to move the phantom, with a black screen displayed on the monitor. iii) Condition 3 Passive touch while viewing other hand: Similar to condition 2, but with a corresponding video from the experimenter displayed on the monitor. iv) Condition 4 Passive touch while viewing own hand: As in conditions 2 and 3, but the video from task 3 in session 1 was shown, with the robotic platform's trajectory altered to match the participant's hand movement.

passive presentation with the addition of visual feedback, both employing active paths recorded previously of the lead author's hand while touching the phantom. Finally, conditions 3 and 4 compared performance when presented visuo-haptic playback of an "other" hand (the lead author's) versus that of one's own hand recorded during the training session.

The four condition blocks were presented in pseudo-random order. Across all experimental blocks, participants listened to white noise on headphones to minimize auditory distraction from the platform motors. A curtain obscured the robotic platform and their own hand from view.

Each block consisted of trials also presented in a pseudo-random order, wherein a tissue phantom embedded with one of three different lump sizes was placed on the robotic platform's end-effector. Each lump size was presented twice, for a total of 6 trials per block. During the trial, participants felt the phantom for 30 seconds, either actively or passively, with the goal of identifying the lump size. Subsequent to each trial, they were asked to identify which of the three lump sizes they felt, rate their confidence in their response (rated on a 5-point Likert scale), and rate the perceived difficulty in identifying the embedded lump sizes (also a 5-point Likert scale).

C. Assessment of Rubber Hand Illusion

Following conditions 3 and 4, in which participants passively felt and watched a palpation, an additional questionnaire was administered to evaluate the extent of their sense of ownership of the hand observed in the video. The employed questionnaire is a modified variant of the standard RHI (Rubber Hand Illusion) questionnaire as referenced in sources [24]–[31], [34]. Responses were elicited from participants using a 5-point Likert scale, where a score of 1 corresponds to "strongly disagree" and 5 to "strongly agree." The questionnaire statements are listed in Table I.

TABLE I
RUBBER HAND ILLUSION QUESTIONNAIRE

No.	Statement
Q1	I felt as if I was looking at my own hand.
Q2	It seems as if my own hand is moving.
Q3	It no longer felt like my right hand belonged to me.
Q4	It felt as if I had no longer a right hand, as if my right hand had disappeared.
Q5	I felt as if the hand on the screen was controlling me.
Q6	I felt as if I was controlling the hand on the screen.
Q7	It seemed as if the hand on the screen had a will of its own.
Q8	It seemed my right hand was in the location where the hand on the screen was.
Q9	It seemed as if the movement I was feeling came from somewhere between my own hand and the hand on the screen.
Q10	It seems like I could not really tell where my right hand was.

Within this questionnaire, items Q1 to Q4 pertain to sensations of ownership and identification with the observed hand. Questions Q5 to Q7 address the feeling of agency and control, while Q8 to Q10 are concerned with spatial perception and proprioceptive drift. The presentation order of these questions was randomized for participants.

IV. Results

A. Lump Size Discrimination

For active touch (condition 1) in the subsequent formal experimental session, each participant was provided with only one lump size at a time and was required to classify it as small, medium, or large. The average accuracy in this condition was 83.3%, indicating that the task of size discrimination, when isolated, presents a more considerable challenge than simultaneous comparison used during training. Nonetheless, this accuracy rate was higher than that seen in all the passive conditions, which had overall accuracies of 75.0%, 71.3%, and 69.4% for Conditions 2-4, respectively. Overall accuracy of identification for different lump sizes was 95.1% for small, 56.9% for medium, and 72.2% for large lumps.

For all four presentation conditions, the discriminatory performance results are shown as confusion matrices in Fig. 8 (a). As lump discrimination is binomial (correct/incorrect for each trial), we performed binary logistic regression to assess the overall impacts of lump size and condition on identification accuracy. We found a highly significant effect of lump size (Wald Chi-Square = 42.4, df = 2, $p < 0.001$), and a marginally significant effect of condition (Wald Chi-Square = 7.3, df = 3, $p = 0.063$).

Thereafter, we conducted pairwise comparisons employing the Wilcoxon signed-rank test with a Holm-Bonferroni correction for post-hoc analysis. Differences in accuracy were significant between all sizes: large versus medium ($p = .0068$), large versus small ($p < 0.001$), and medium versus small ($p < 0.001$). Although our regression test indicated only marginal significance of Condition, potential impact of passive versus active is suggested by significant differences only

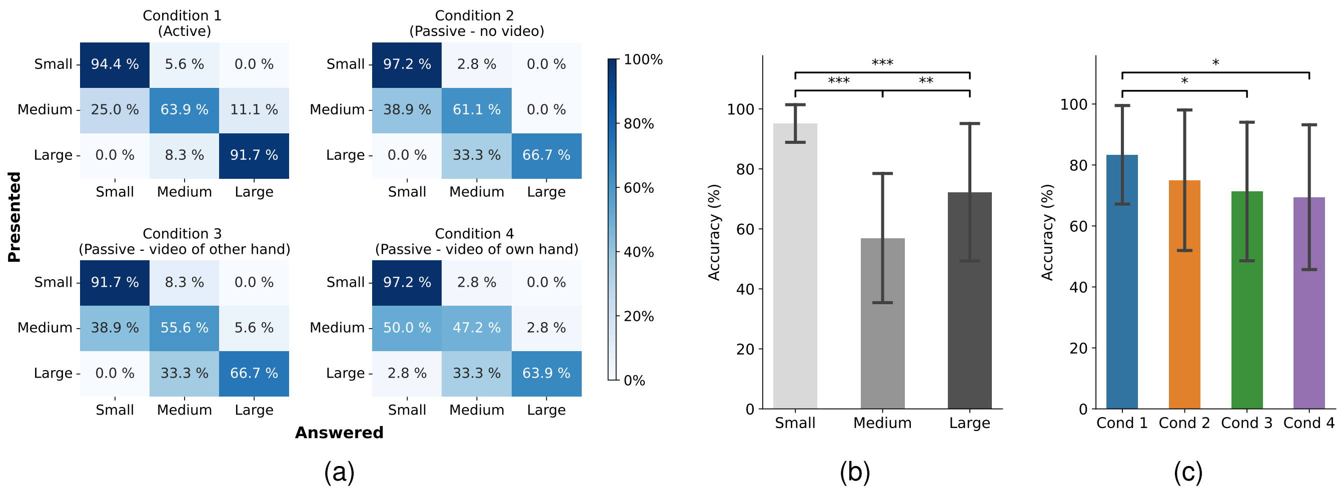

Fig. 8. **Accuracy performance.** (a) Confusion Matrix. (b) Average accuracy percentages across sizes were 95.1% in small size, 56.9% in medium size, and 72.2% in large size. (c) Average accuracy percentages across conditions were 83.3% in condition 1, 75.0% in condition 2, 71.3% in condition 3, 69.4% in condition 4.

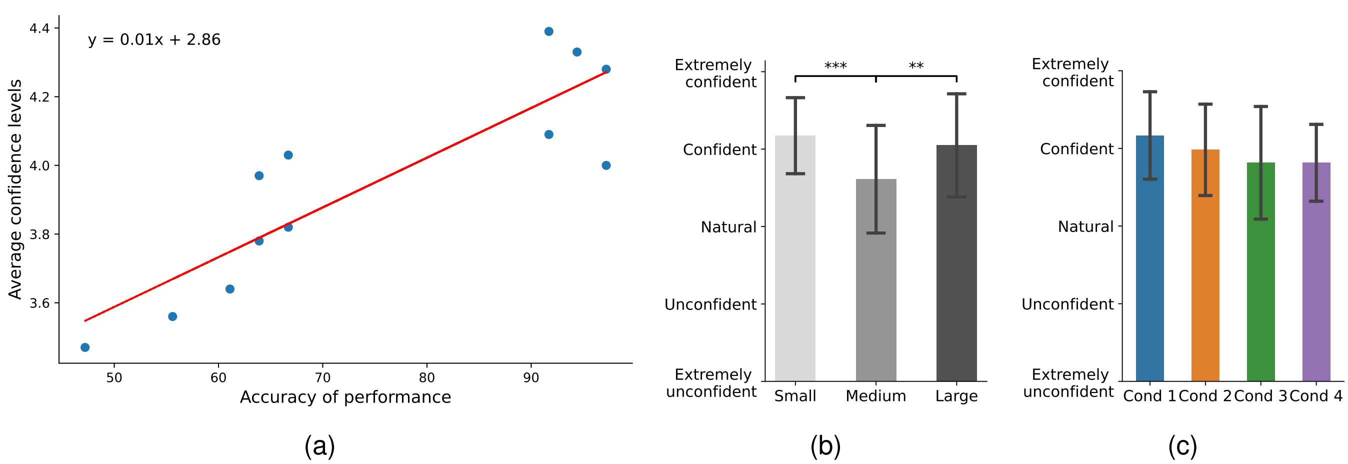

Fig. 9. **Confidence level.** (a) Least Square linear regression analysis of the accuracy of performance in relation to the corresponding average confidence levels. R-squared = 0.76. (b) Average confidence levels across sizes were 4.2 in small size, 3.6 in medium size, and 4.0 in large size. (c) Average confidence levels across conditions were 4.2 in condition 1, 4.0 in condition 2, 3.8 in condition 3, 3.8 in condition 4.

between Active versus Condition 3 ($p = 0.035$) and Active versus Condition 4 ($p = 0.017$). Results are summarized in Fig. 8 (b)-(c).

B. Participant Confidence and Perceived Difficulty

TABLE II
AVERAGE CONFIDENCE LEVELS (MEAN ± SD) FOR DIFFERENT SIZES AND CONDITIONS

	Small	Medium	Large
Condition 1	4.33±0.52	3.78±0.45	4.39±0.55
Condition 2	4.28±0.48	3.64±0.50	4.03±0.47
Condition 3	4.09±0.50	3.56±0.49	3.82±0.48
Condition 4	4.00±0.46	3.47±0.52	3.97±0.51

Judgements of perceived difficulty were remarkably similar across all conditions and lump sizes, suggesting that this was either unaffected by experimental conditions, or not a meaningful question to participants. In contrast, Confidence levels varied more widely and are summarized in Table II, with 1 corresponding to ”Extremely Unconfident” and 5 to ”Extremely Confident.”

On the whole, participants’ confidence hovered near the value of 4, corresponding to ”Confident.” Participants consistently exhibited diminished confidence when faced with medium-sized lumps or under the visio-haptic passive conditions 3 and 4, which also correspond to lower accuracy rates. To elucidate the correlation between confidence and accuracy performance, a linear regression model (see Fig. 9 (a)) was applied to align the compare confidence data from Table II with average accuracies, demonstrating an R-squared value of 0.76.

Chi-squared tests demonstrated that lump size once again has a highly significant impact on Confidence ratings (Chi-square = 34.96, df = 8, $p-value < 0.001$), but Condition had no effect (Chi-square = 14.84, df = 12, $p-value = 0.2503$). Post-hoc analysis using the Wilcoxon signed-rank test with Holm-Bonferroni correction showed that only the medium size

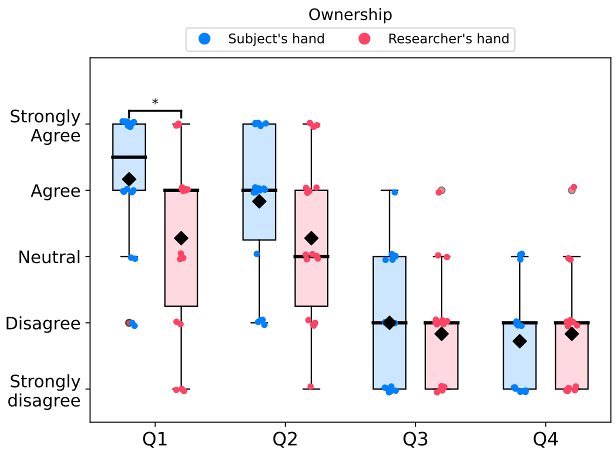

Fig. 10. **Questionnaire results: ownership.** First 4 statements from the questionnaire: Q1. "I felt as if I was looking at my own hand." Q2. "It seems as if my own hand is moving." Q3. "It no longer felt like my right hand belonged to me." Q4. "It felt as if I had no longer a right hand, as if my right hand had disappeared."

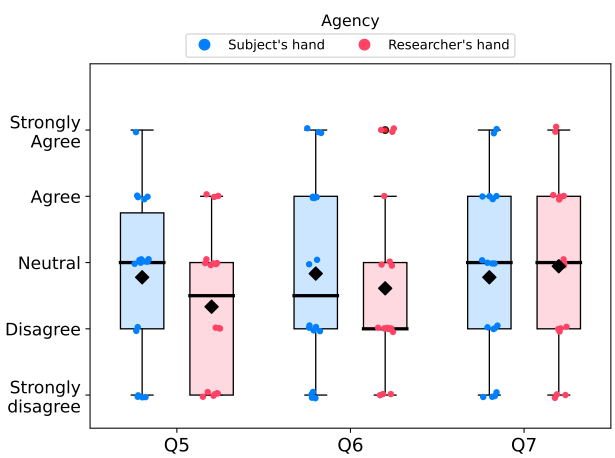

Fig. 11. **Questionnaire results: agency.** 5th to 7th statements from the questionnaire: Q5. "I felt as if the hand on the screen was controlling me." Q6. "I felt as if I was controlling the hand on the screen." Q7. "It seemed as if the hand on the screen had a will of its own."

resulted in significantly lower confidence ratings than the small ($p = 7.99 \times 10^{-7}$) and large ($p = 0.0015$) lump sizes.

C. Rubber Hand and Kinesthetic Illusions

Results from the rubber-hand illusion questionnaire are depicted in Figs. 10–12. We applied Wilcoxon signed-rank tests to each questionniare result across the two passive conditions with visual feedback (Conditions 3 and 4). This analysis demonstrated a single significant difference between the two conditions for the first question ($p = 0.042$), indicating that observing one's own hand (condition 4) versus another's hand (condition 3) did elicit a distinct impact on the participants' experience. Beyond this, no other significant differences were identified for the remaining eight questions between the two conditions, suggesting that participants harbored similar experiences concerning these facets of the RHI experience, irrespective of the differing hands showcased in the videos.

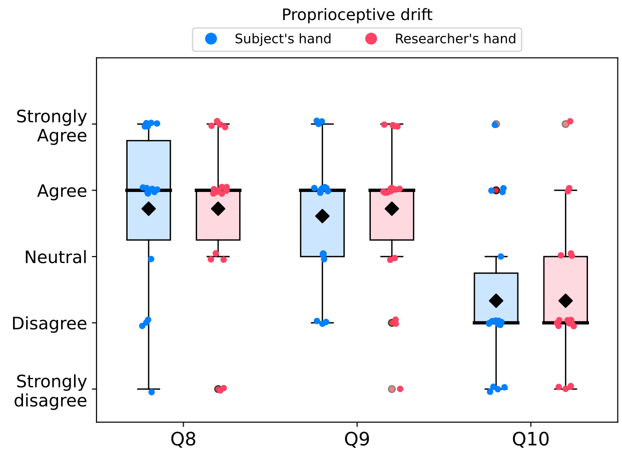

Fig. 12. **Questionnaire results: proprioceptive drift.** 8th to 10th statements from the questionnaire: Q8. "It seemed my right hand was in the location where the hand on the screen was." Q9. "It seemed as if the movement I was feeling came from somewhere between my own hand and the hand on the screen." Q10. "It seemed like I could not really tell where my right hand was."

V. Discussion

In our participant study, we used a custom robotic platform to explore two primary questions. Firstly, will a person's tissue examination performance be affected by the absence of their own active movement, and are there presentation conditions that can mitigate losses in performance? Additionally, can the rubber hand illusion and kinesthetic illusion be simultaneously induced by rendering synchronized visuo-tactile feedback? This second question affected the first, as we wished to explore if RHI could improve immersiveness and therefore perceptual performance.

A. Passive Palpation Performance

During the training session, all 18 participants could perfectly distinguish the three lumps when actively felt side-by-side. During the experimental active touch condition, however, the average accuracy of size identification was 83.3%. This decline in accuracy between the training and experimental session can be ascribed to increased difficulty in distinguishing sizes in absence of a reference; during experiments, only a single concealed tissue phantom is accessible at one time, as opposed to all three simultaneously during training. Furthermore, identification and confidence for the medium-sized lump was significantly lower than that for the small and large lumps. indicating that without reference sizes, participants struggle more to identify lump size from nearest neighbor sizes. Regardless, active performance overall was superior to that for all passive conditions.

Video feedback, contrary to our expectations, resulted in significantly worse performance for both conditions 3 and 4 compared to active touch. We anticipated that video assistance could provide additional information about relative motion and possibly enhance a sense of immersion through a kinesthetic illusion, thereby enhancing diagnostic accuracy and confidence. Instead, visual feedback might distract participants from focusing on haptic sensations, or visual feedback that shows active hand motion that differs from actual lack of passive hand motion may increase confusion. Similar performance between conditions 1 (active) and 2 (passive, no visual) indicate that our current method of haptic display provides adequate information about relative motion through haptic channels alone; visual feedback of relative motion may still be required for passive haptic interfaces that provide reduced haptic feedback.

A comparative analysis between conditions 3 and 4 gives insights into the palpation strategies for passive touch. In condition 3, the participant views and experiences active exploration of the lead author's hand, while in condition 4 they view playback of their own hand recorded during the training session. Despite the less familiar-looking hand in condition 3, participants performed insignificantly better than when viewing playback of their own hand. While this again ran contrary to our expectations, we suspect this is due to non-optimal exploration strategies employed by the novice participants during their training session. The recorded motion and video used in condition 4 was from the lead author who had developed practiced and increasingly optimized search strategies during experimental development, highlighting the importance of expertise in specialized haptic tasks.

B. Ownership and Kinesthetic Illusions

Traditional techniques for inducing an ownership illusion, i.e. rubber hand illusion, depend on synchronous motion and stimulation of the visible artificial hand with the hidden hand, driven either by the participant or the experimenter [27], [28]. Kinesthetic illusions, in which a stationary hand feels as though it moving, can be generated through isolated tendon vibration, touch, or vision. Our setup instead leveraged synchronous haptic feedback to the stationary hand with visual feedback of the moving hand in an attempt to induce both illusions. Findings from our illusion questionnaire indicate presence of both ownership and kinesthetic illusions, specifically in the agreement to Questions 2: "It seems as if my own hand is moving" and 8: "It seemed my right hand was in the location where the hand on the screen was." Intriguingly, participants also reported high agreement with question 9: "It seemed as if the movement I was feeling came from somewhere between my own hand and the hand on the screen." This observation represents an intermediate stage of proprioceptive drift, possibly attributable to the more than 40 cm separation between the subject's hidden static hand and the visible moving virtual hand, leading to confusion. The only significantly different questionnaire response between the passive video conditions was for question 1: "I felt as if I was looking at my own hand," indicating that participants could indeed identify if the video hand was actually theirs. The otherwise similar questionnaire outcomes across conditions affirm that individuals can feel some embodiment of the video hand even when they are stationary and observing someone else's hand, despite no increase in diagnostic performance.

C. Implications for Future Passive Displays

Our initial study looked at the impact of supplemental visual display to enhance passive perception when touching a real object. While those objects were palpable tissue phantoms in our current study, this work could be extended to any environment in which a user may wish to monitor haptic sensations collected by a robot or another person. For example, we envision applications in learning or monitoring correct tool usage and dexterous manufacturing tasks. Eventually, it is not feasible to move real objects relative to the passive hand; rather, we anticipate that captured haptic data can be displayed through a haptic glove or other display. Further work is needed to understand the role of visual feedback in these contexts, as well as impact of additional features such as passive hand posture and motion.

D. Limitations

Several limitations within our study warrant resolution in future work. Primarily, our platform is limited in the sensations it can display due lack of vertical motion and force control. The 2D nature of the display limits trackable movement to sliding touch, and lack of force-control prevents accurate display of variable stiffness sensations. Future research encompassing a broader range of haptic features, including texture, stiffness, location, shape, and mobility, require additional dimensions of display and hand posture.

There were also limitations in our experimental protocol. Absolute lump size detection was difficult for our participants, and future work may detect more nuanced performance differences using comparative tasks, such as choosing which lump is larger. Regarding video feedback, we did not record participants' skin color or the degree to which their hand matched the physical appearance of the "other" hand in condition 3. Potential mismatch in hand color or shape may have affected strength and onset time of RHI [49]. Future research could mitigate this problem by requiring everyone to wear gloves or using only grayscale video, potentially isolating and reducing potential mismatch of hand appearance. Additionally, we did not have an experimental condition in which visual and tactile feedback were asynchronous; therefore, evaluating the extent of advantages conferred by the ownership and kinesthetic illusions becomes challenging. Although agency and ownership were compared across conditions 4 and 3 (own vs "other" hand), an asynchronous condition between visual and tactile feedback could give additional insight into contribution of the illusions to task performance itself.

VI. Conclusion

This study explored different passive presentation techniques for communicating an active palpatation task, using a robotic platform that can provide a passive hand with visual and haptic feedback recorded from an active hand. While we observed slight decreases in perceptual acuity and confidence across all passive presentation conditions, many participants did experience sizable ownership and kinesthetic illusions from synchronized visio-haptic feedback during passive presentation. Our results suggest promise for creating a sense of immersion to a passive viewer of active hands-on experiences, although additional methods for improving diagnostic performance under passive conditions must be explored. Going forward, we will explore performance and immersion under a broader range of tasks and passive conditions.

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