Wearable fingertip with touch, sliding and vibration feedback for immersive virtual reality

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***Abstract*—Wearable haptic technology plays a key role to enhance the feeling of immersion in virtual reality, telepresence, telehealth and entertainment systems. This work presents a wearable fingertip capable of providing touch, sliding and vibration feedback while the user interacts with virtual objects. This multimodal feedback is applied to the human fingertip using an array of servo motors, a coin vibration motor and 3D printed components. The wearable fingertip uses a 3D printed cylinder that moves up and down to provide *touch feedback*, and rotates in left and right directions to deliver *sliding feedback*. The direction of movement and speed of rotation of the cylinder are controlled by the exploration movements performed by the user hand and finger. *Vibration feedback* is generated using a coin vibration motor with the frequency controlled by the type of virtual material explored by the user. The Leap Motion module is employed to track the human hand and fingers to control the feedback delivered by the wearable device. This work is validated with experiments for exploration of virtual objects in Unity. The experiments show that this wearable haptic device offers an alternative platform with the potential of enhancing the feeling and experience of immersion in virtual reality environments, exploration of objects and telerobotics.**

***Index Terms*—haptics, multimodal feedback, immersion**

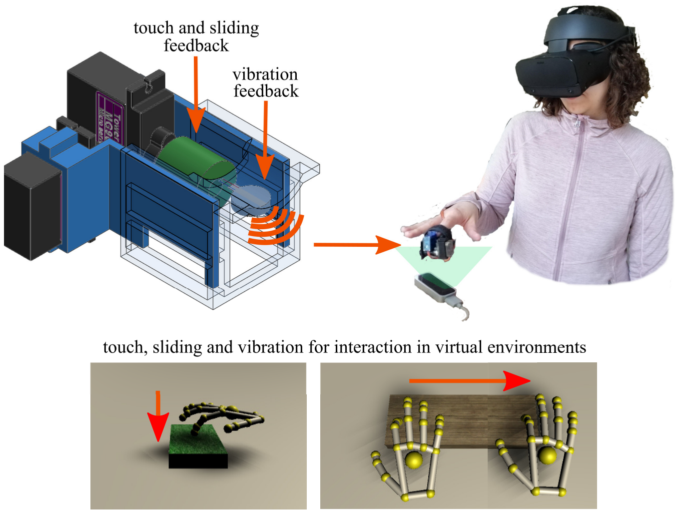

Fig. 1. Wearable fingertip with an array of servo motors, a coin vibration motor and 3D printed elements to provide touch, sliding and vibration feedback during the interaction and immersion in virtual environments.

I. Introduction

Haptic devices have the potential to enhance the feeling and experience of immersion and interaction in virtual reality, augmented and remote environments. Common applications where haptics plays a crucial role are telepresence, telerobotics, healthcare, assembly and disassembly in manufacturing and the entertainment industry [1]–[3]. In recent years, researchers have developed wearable devices capable of providing vibration, touch, force and temperature feedback to the human hands and fingers based on the advances in sensor technology, materials and electronics [4]–[7].

Particularly, researchers have focused on lightweight and compact wearable haptic devices to provide feedback to the human fingers while interacting with virtual objects. For instance, miniature DC motors have been used in wearable devices to apply shear and force on the human fingertips [8]. Normal and shear forces, and slip sensation have been generated on the human fingers using compact wearable devices composed of movable belts, soft materials and servo motors [9], [10]. Stiffness feedback from virtual objects has been achieved with a 3-DoF wearable finger using three servo motors, a vibration motor and a mobile platform [11].

Haptic feedback from virtual environments has been explored using HTC VIVE and Oculus Rift controllers, together with gearboxes and servo motors. This approach has been used to create the feeling of object slip and texture exploration applying lateral forces that deform the skin of the fingertip [12], [13]. These interfaces have been also employed to render touch, shear force and texture haptic sensations [14], [15]. However, these haptic devices tend to be bulky, they do not provide continuous sliding or shear forces and they need to be hold by the user at all times, limiting the use the fingers for interaction and exploration.

In this work, a wearable fingertip device capable of providing multimodal haptic feedback based on touch, sliding and vibration is presented (Figure 1). This multimodal feedback is generated according to the hand and finger movements while exploring objects in the virtual reality environment. Touch and sliding feedback are applied to the fingertip using a 3D printed cylinder element, which moves up and down and rotates continuously when the user performs touch and sliding movements. This cylinder is actuated by miniature servo motors, which have shown to be reliable for wearable

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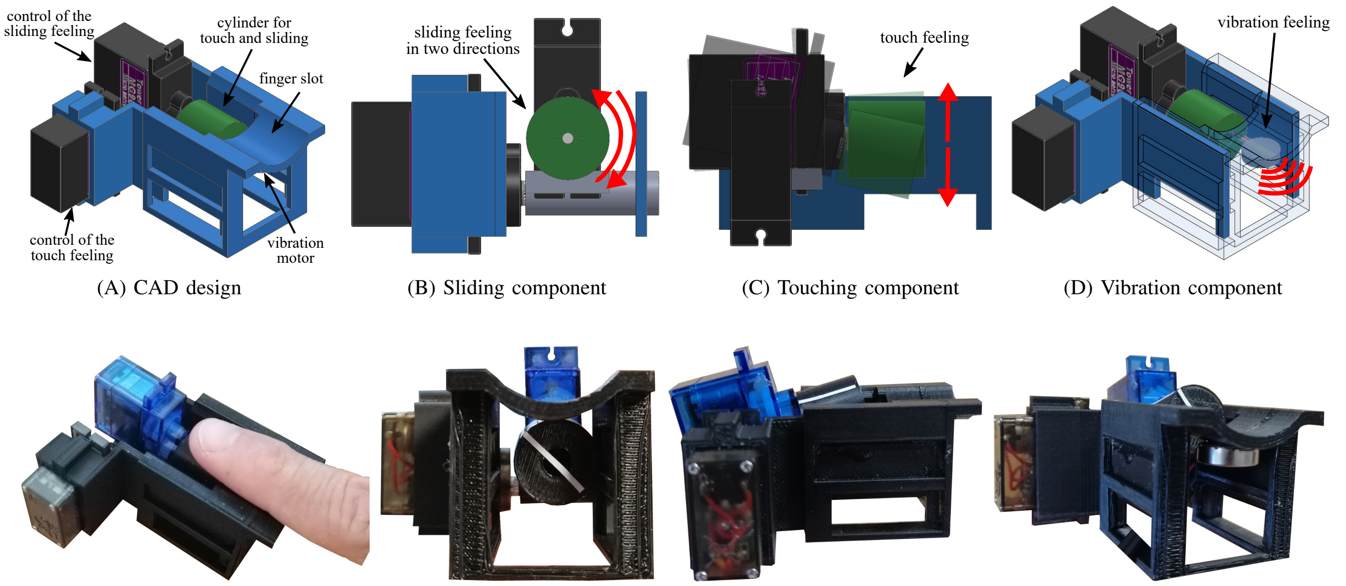

(A) CAD design (B) Sliding component (C) Touching component (D) Vibration component

(E) 3D printed wearable device (F) 3D printed device - sliding (G) 3D printed device - touching (H) 3D printed device - vibration

Fig. 2. CAD and 3D printed wearable fingertip. (A) CAD design with all the components of the wearable fingertip device. (B) Sliding feedback with a cylinder that rotates in left and right directions. (C) Touch feedback with a cylinder that moves up and down. (D) Vibration feedback with a coin vibration motor. (E)-(H) 3D printed wearable fingertip with components to provide multimodal haptic feedback.

devices [16], [17]. A coin vibration motor mounted on the wearable device creates vibration feedback on the fingertip according to the material of the virtual object being explored. This approach makes the proposed wearable haptic device capable of proving multimodal feedback, compact, lightweight and it does not restrict finger movements.

The wearable haptic device is validated with experiments in virtual reality environments in Unity, where the hand and fingers of the user are tracked with the Leap Motion controller. The user is asked to press buttons and slide their finger over textures to receive touch, sliding and vibration feedback. Individual and combined feedback applied on the fingertip are also tested to evaluate the performance and reliability of the wearable device, but also to observe the potential of combining multimodal feedback to enhance the feeling of immersion and interaction with virtual objects.

Overall, the results show the capability of the proposed wearable haptic device to provide touch, sliding and vibration sensation on the human fingertip for an enhanced immersion and interaction with objects in virtual reality environments.

II. Methods

A. Wearable fingertip device

The wearable fingertip device is designed to provide multimodal haptic feedback based on sliding, touch and vibration using miniature servo motors, 3D printing components and a coin vibration motor (Figure 2A).

1) Sliding: This type of feedback is generated by the application of continuous lateral force on the skin of the human fingertip, that creates the feeling of sliding the finger over an object. This sliding sensation is generated using a 3D printed cylinder capable of rotating in left and right directions while being in contact with the fingertip (Figure 2B). The cylinder has dimensions of 15 mm diameter and 15 mm length, and it has been fabricated using polylactic acid (PLA) material. The sliding cylinder is attached to the FS90R continuous miniature servo motor, from FEETECH, which is responsible for rotating the cylinder in left and right directions.

2) Touch: This feedback modality is applied by pressing the skin of the human fingertip, creating the feeling of being touching an object. Touch sensation is delivered using the 3D printed cylinder, described in the previous section, to perform up and down movements to press and move away from the fingertip (Figure 2C). The cylinder is attached to the MG90S miniature servo motor, from TowerPro, which is responsible for moving the cylinder up and down for the generation of touch feedback. This servo motor is precisely coupled, controlled and synchronised with the motor responsible for providing sliding feedback. This approach allows the wearable haptic device to provide reliable touch and sliding feedback to the human fingertip according to the interaction with objects in virtual reality environments.

3) Vibration: This generation of vibration feedback on the human fingertip, together with touch and sliding feedback, can create the feeling of exploring different object materials. Vibration feedback is applied on the human fingertip using a coin vibration motor, from Precision Microdrives, attached under the finger slot of the wearable device as shown in Figure 2D. This vibration motor can achieve a maximum frequency of 280 Hz. The vibration frequency applied on the fingertip can be controlled to create the sensation of being touching and exploring objects with different properties such as roughness and type of material in virtual environments.

B. Fingertip motion tracking

The human hand and finger movements are accurately tracked using the Leap Motion controller, from UltraLeap, which employs an optical sensing tracking approach (Figure 3A). Other works have also employed marker-based high speed vision systems and Head-Mounted Displays (HMD)

(A) Hand and fingertip tracking (B) Vertical fingertip tracking (C) Horizontal fingertip tracking

Fig. 3. Leap Motion controller for tracking the hand and fingertip position and speed. (A) Tracking area with the wearable haptic device. (B) Vertical movement used together with touch and vibration feedback. (C) Lateral movement employed together with touch, sliding and vibration feedback.

systems for tracking the human body [13], [18]. The information from the Leap Motion controller about the hand and finger position ($x-$, $y-$, and z axes) is used to detect when a virtual object in Unity is being touched and explored by the human. Changes in the z axis, detected by the Leap Motion module, are used by the wearable fingertip device to control the position of the 3D printed cylinder moving it up and down. This process creates the sensation of touching and pressing virtual objects with the human fingertip (Figure 3B). Similarly, changes in x and y axes, detected by the Leap Motion module, are employed by the wearable fingertip device to control the speed and direction of rotation of the 3D printed cylinder. This process creates the sensation of sliding the human fingertip at different speeds and directions over the surface of virtual objects (Figure 3C).

C. Control architecture of the wearable fingertip

Control and delivery of touch, sliding and vibration feedback with the wearable fingertip device is achieved by the interconnection of the modules shown in Figure 4. These modules control the wearable device using data from the Leap Motion controller such as hand and finger positions, movement speed and direction of the user and information about position and dimensions of virtual objects in Unity.

The wearable device detects collisions with objects in the virtual reality environment by tracking the position of the human finger using the Leap Motion, and comparing it with the position of the object in Unity. The collision detection process allows the wearable device to determine when the fingertip is touching an object in the virtual environment. When a touch or collision event is detected, the *touch signal* is sent to the servo motor responsible for moving the 3D printed cylinder up to contact the human fingertip, and create the sensation of being touching the virtual object. When no touch or collision event is detected, the *no-touch signal* is sent to the servo motor to move the cylinder down and away from the fingertip. This process for collision detection and touch feedback is shown in green colour in Figure 4.

Detection of lateral hand and finger movements using the Leap Motion controller allows the wearable device to determine the direction (left or right) of sliding feedback to be delivered. This information, together with the movement speed extracted from the tracking process by the Leap Motion module, allows the control of the direction of rotation and speed for the servo motor attached to the 3D printed cylinder. The *sliding signal*, composed of direction and speed information, is sent to the servo motor responsible

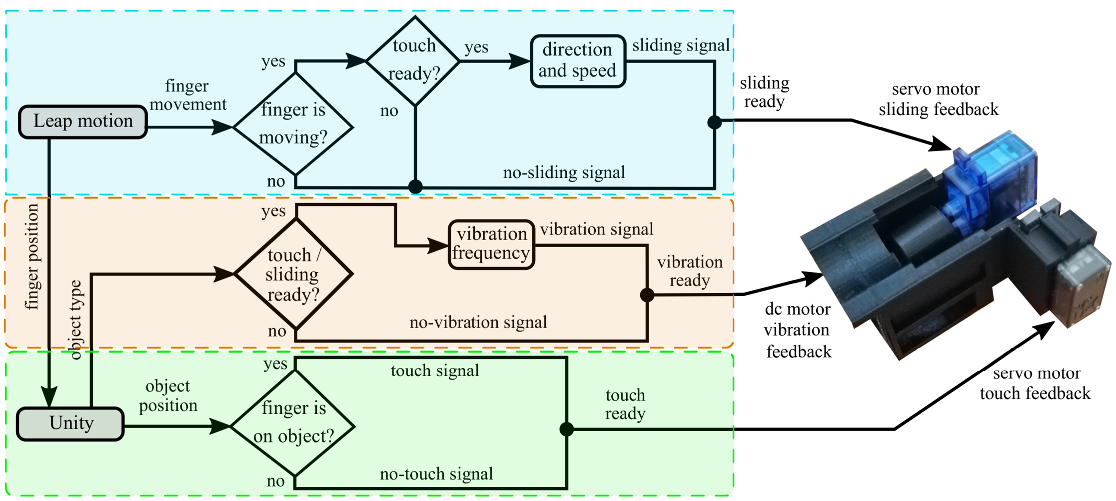

Fig. 4. Control architecture composed of modules for control of the wearable fingertip device for multimodal haptic feedback. The control modules grouped into three layers for touch (green layer), sliding (blue layer) and vibration (orange layer) feedback employ data from the hand tracking process and the position and material of the objects being explored in Unity.

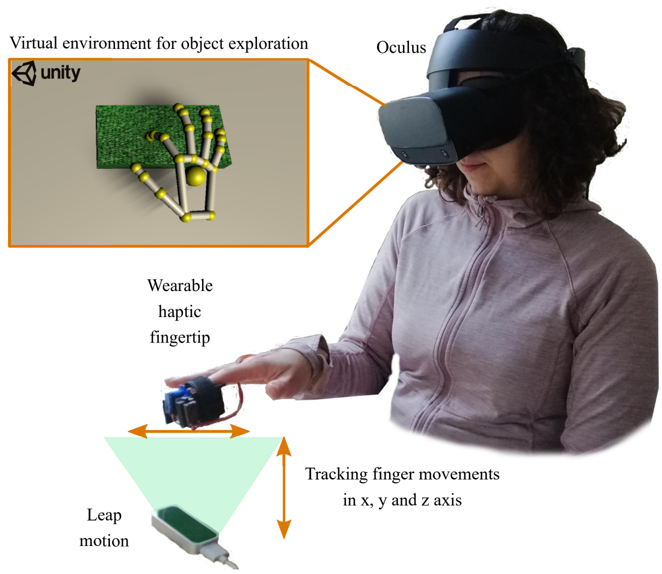

Fig. 5. Experimental setup composed of the wearable haptic device, Leap Motion Controller and Oculus Rift headset. This setup is used to validate the wearable fingertip to provide touch, sliding and vibration feedback with object exploration experiments in immersive virtual reality environments.

for rotating the cylinder to deliver the corresponding sliding feedback. The sliding stimulus is active only when the signal *touch ready* is *true*, which indicates that the fingertip is touching an object. Otherwise, when the fingertip is not touching an object, the signal *touch ready* is *false*, and the sliding feedback is not generated even if the user performs lateral hand movements. When no lateral movement is detected with the human fingertip, the *no-sliding signal* is used to stop the servo motor. The control of the sliding feedback is shown in blue colour in Figure 4.

Vibration feedback can be generated when a touch event between the fingertip and a virtual object is detected (*touch ready* is *true*), and when lateral hand and finger movements are performed by the user sliding the fingertip on an object (*sliding ready* is *true*). The *vibration signal* is sent to the coin vibration motor, placed under the fingertip slot in the wearable device, to generate vibration feedback. When no touch or lateral events are detected the *no-vibration signal* is sent to stop the coin vibration motor. The vibration frequency of the motor ranges from 0 Hz to 280 Hz and they can be precisely defined and controlled to create the feeling of being exploring objects with properties such as roughness and texture. The module and signals of this feedback modality are shown in orange colour in Figure 4.

D. *Visual immersion with VR headset*

The wearable fingertip device is employed together with the Virtual Reality (VR) headset Oculus Rift, by Oculus VR, to allow the user to immerse visually in the virtual reality environment developed in Unity. This immersive modality is employed in the experiments to allow the users to observe their virtual hands, fingers and different virtual objects for exploration while wearing the proposed multimodal haptic device. Figure 5 shows the wearable haptic device, the Oculus VR headset and Leap Motion Controller employed together for experiments of immersion in virtual environments. This experimental setup can also be used to observe the effect and contribution from each haptic feedback modality (sliding, touching, vibration) for enhancing the feeling and experience of immersion in virtual reality environments.

III. Experiments and Results

This section presents the experiments with virtual objects to validate the capability of the wearable device to provide multimodal feedback to the human fingertip. The experiments were carried out with five participants.

A. *Touch and vibration stimuli*

In the first experiment, the participants were asked to press three buttons in a virtual reality environment, developed in Unity, while wearing the haptic device and Oculus headset (Figure 6). The buttons were programmed to sent vibration feedback (blue button), touch feedback (green button) and combined touch and vibration feedback (red button). Touch and vibration feedback were enabled only when contact between the fingertip and object was detected as shown in the control architecture in Figure 4. The height of the buttons also changed when they were pressed making the interaction more realistic. This experiment is used to validate the wearable device to deliver multimodal feedback, but also to observe their affect on the feeling of immersion and interaction with virtual objects. First, participants were asked to press the blue button to receive only vibration feedback with the coin vibration motor mounted on the wearable device. Second, participants were asked to press the green button to receive only touch feedback with the 3D printed

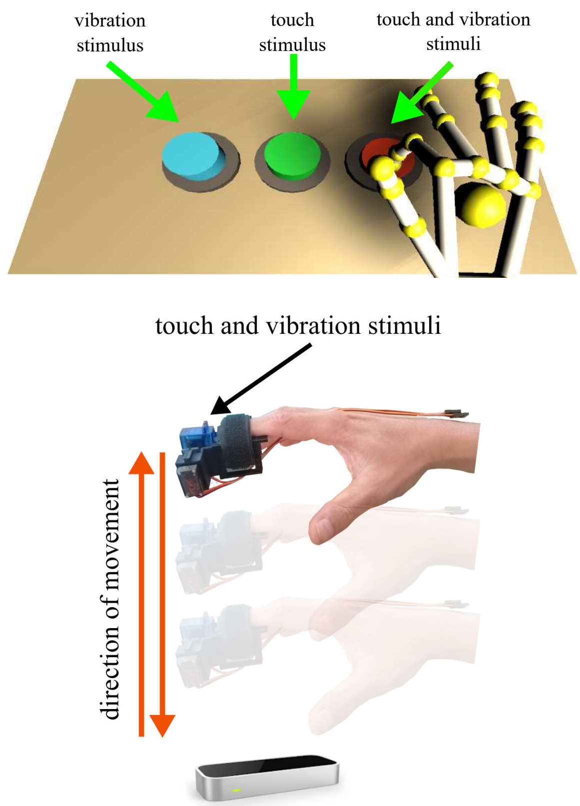

Fig. 6. Experiments for object exploration in immersive virtual reality environments based on pressing buttons. These buttons send to the user feedback based on vibration, touch and combined feedback.

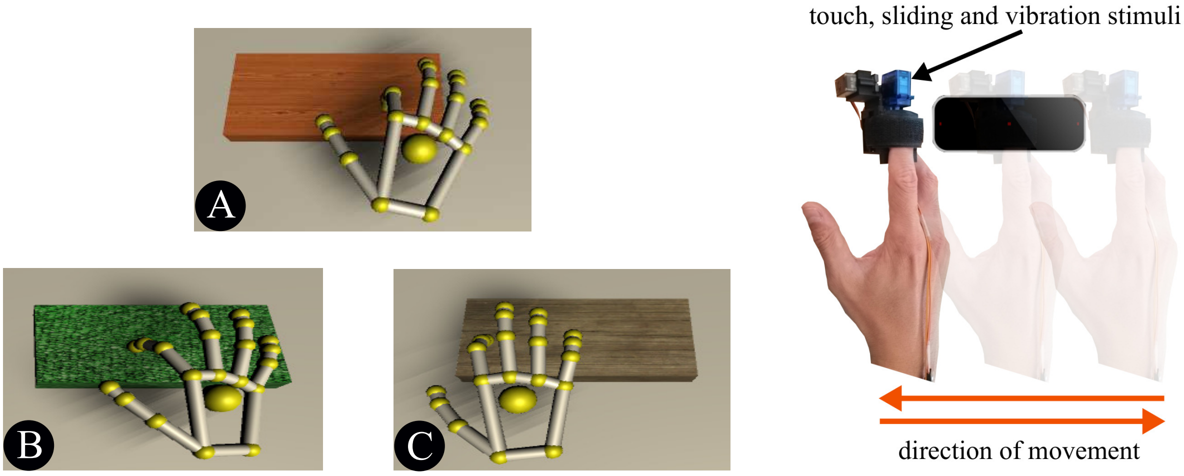

Fig. 7. Experiments for object exploration in immersive virtual reality environments based on lateral hand and finger movements. The user receives vibration, touch and sliding feedback while exploring the objects. This experiment is also used to observe the feeling of exploring objects with materials A, B and C using touch, sliding and vibrations with different frequency values.

cylinder. Then, participants pressed the red button to receive both touch and vibration simultaneously on their fingertip. This experiment was repeated 10 times by each participant.

The participants were asked to indicate, in a range of 1 to 10, the level of immersion perceived for each feedback modality while pressing the buttons. The results in Figure 8A show that touch feedback provided an enhanced feeling of pressing a button over the immersion feeling achieved by vibration alone. Combination of touch and vibration shows a slight reduction in the feeling of immersion compared to touch feedback alone. This reduction can be related to the type of experiment of pressing buttons, where it is likely that participants would expect to feel only touch or contact on their fingertips rather than vibrations. These results also shows the capability of the wearable device for providing multimodal haptic feedback that can contribute to enhance the feeling of touching virtual objects.

B. vibration, touch and sliding stimuli

In the second experiment, participants were asked to touch and slide their fingertip over virtual objects with different materials. This experiment was used to validate the wearable device for delivering sliding, touch and vibration and to observe their effect in the feeling of immersion and interaction (Figure 7A). First, only vibrations at a constant frequency were sent to the fingertip while exploring the object with lateral hand movements. Second, only touch feedback was sent to the fingertip while repeating the lateral exploration task on the object. Third, touch and sliding feedback were sent simultaneously to the fingertip while sliding the finger over the virtual object. Fourth, the participants repeated the experiment to receive vibration, touch and sliding feedback simultaneously. Each feedback modality was enabled when contact between the fingertip and object was detected as shown in the control architecture in Figure 4. The wearable fingertip device can provide sliding feedback at different speeds, which allows participants to perform sliding movements at different speeds over the virtual objects. Each participant performed 10 repetitions of the experiments.

The participants were also asked to indicate, in a range of 1 to 10, the level of immersion perceived while exploring the rectangular objects using lateral movements and receiving vibration, touch and sliding feedback. The results in Figure 8B show that vibration feedback alone achieved

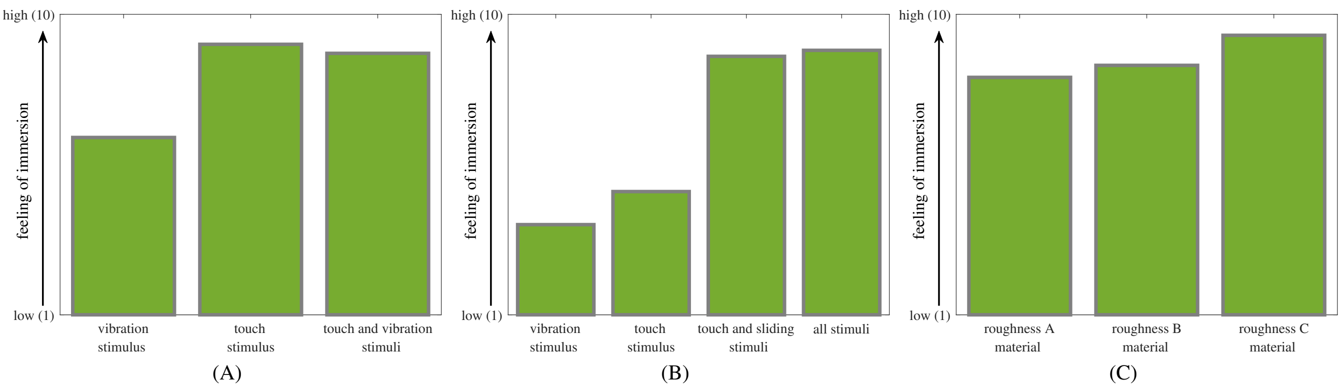

Fig. 8. Results from the feeling of immersion and exploration of objects in virtual reality environments using the wearable fingertip device. (A) Level of feeling of immersion with vibration, touch and combined touch and vibration feedback while pressing virtual buttons. (B) Level of immersion using vibration, touch and sliding feedback while exploring virtual objects with lateral hand movements. (C) Level of immersion and perception of textures using touch, sliding and vibration with different frequencies and lateral hand movements.

the lowest feeling of immersion, while touch and sliding feedback allowed the user to perceive an enhanced feeling of immersion and interaction with the virtual objects. The enhanced feeling of immersion is expected given that the skin of the fingertip is deformed by the wearable device in a similar way to when the fingertip slides on a real object. This experiment also shows that the use of vibrations with touch and sliding feedback achieved a slight increment in the feeling of being exploring an object.

The capability of the wearable device for providing vibrations at different frequencies, together with touch and sliding feedback, was also validated for object exploration. This experiment based on vibrations is commonly performed to create the feeling of exploration of textures [19], [20]. In this experiment, rectangular objects covered with virtual textures were used to observe the effect of the different vibration frequencies, touch and sliding feedback in the perception of textures in the virtual environment (Figure 7A,B,C). Participants performed the exploration of three objects with different textures using lateral hand movements while vibration, touch and sliding feedback were applied on the fingertip. Predefined vibration feedback with frequencies of 50 Hz, 100 Hz and 150 Hz were used for exploration of objects with textures A, B and C, respectively, shown in Figure 7C. This experiment was repeated 10 times by each participant. The results from this experiment shown in Figure 8C indicate that vibration, touch and sliding together can contribute to enhance the feeling of being touching different textures.

Overall, the results from the experiments show that the proposed wearable fingertip device is capable of reliably delivering individual and combined touch, sliding and vibration feedback to the human fingertip. This type of wearable devices can enhance the feeling of immersion and interaction in virtual reality environments, but also in applications such as telepresence, telerobotics and gaming.

IV. Conclusion

This work presented a wearable fingertip device that can provide multimodal feedback based on vibration, touch and continuous sliding for immersion in virtual reality environments. This device was built using an array of miniature servo motors, a coin vibration motor and 3D printed components. Each feedback modality was applied on the human fingertip according to the type of hand and finger movements (vertical or lateral) performed by the user while exploring virtual objects. Hand and finger movements were tracked in real-time using the Leap Motion controller interfaced to Unity. Experiments based on touching and sliding the fingertip over virtual objects were performed to validate the wearable fingertip for reliable multimodal haptic feedback. The results showed that the device can provide touch, vibration and continuous sliding feedback reliably as well as individual and combined feedback to enhance the feeling of immersion and interaction in virtual reality environments. Overall, this work presented an alternative wearable fingertip device with reliable multimodal haptic feedback that can be used in applications such as immersion and telepresence, telerobotics, human-robot interaction and gaming.

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