A Lightweight Haptic Feedback Glove Employing Normal Indentation, Lateral Skin Stretch and both Softness and Hardness Rendering

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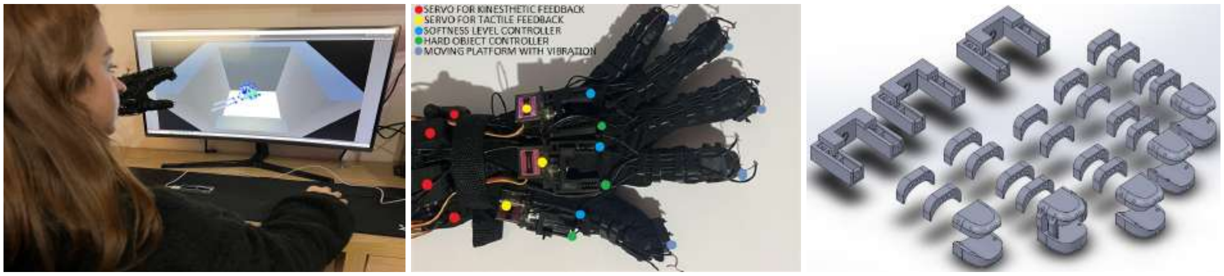

Figure 1: (a) The experimental setup (b) Haptic glove overview (c) 3D-printed glove parts

ABSTRACT

Current haptic devices often provide tactile feedback via only vibrations and kinesthetic feedback based on heavy and cumbersome exoskeletons hindering users' motion. This paper presents an innovative, lightweight, flexible and easy-to-wear haptic glove providing realistic tactile feedback through normal indentation and lateral skin stretch in addition to vibrations, as well as high-fidelity kinesthetic feedback through strings pulled by servo motors. Unlike current systems, it is inexpensive and tactile feedback is achieved through small vibration motors embedded on the fingertips of the glove. Normal indentation and shear forces are created through moving platforms applying pressure to the skin. Kinesthetic feedback is provided by small strings attached to the glove and pulled to simulate, unlike previous systems, both soft and hard virtual object manipulation. The glove is controlled by a small microcontroller receiving input from a computer sending commands to the motors and actuators. Study results suggest that the user is capable to perceive better directional information and surface geometry when vibration is added to the fingertip. Users perform better at distinguishing softness levels when the differences in softness are distinct.

1 INTRODUCTION

Haptic technology creates the illusion of touch, pressure and other tactile sensations through mechanical, electrical, or other forms of energy, in robotics, virtual reality (VR), teleoperation, rehabilitation, cultural heritage etc [27], [24]. Haptics in VR enhances immersion [23] [39]. In teleoperation, haptic feedback provides a sense of touch and force of the remote environment [31], [1], [30]. In rehabilitation, haptic systems provides patients with a sense of touch and movement, recovering their senses [16], [9]. Wearable haptic systems, though, are often heavy, failing to communicate touch as in the real world, therefore, simulation fidelity is low. Haptics is interlinked with many open research questions in relation to hardware configurations for perceptually accurate haptic sensations [29]. Tactile feedback refers to the sense users feel in their fingers through vibrations, normal indentation, lateral skin stretch, and shear forces [37], [36]. Kinesthetic feedback is the sense from sensors in muscles, joints and tendons, achieved through exoskeletons [20], pneumatic modules [38] and by pulling strings attached to fingers [19]. Users feel a sense of texture, shape, and weight of the virtual objects [18]. Haptic devices providing tactile feedback often employ solely vibrations; just one of the cutaneous sensation primitives, the others being normal indentation, lateral skin stretch and relative tangential motion [25], [5]. Kinesthetic feedback is provided through heavy systems impairing users' motion [28]. With rigid exoskeletons, perception of soft objects is nearly impossible [20]. With strings, relevant systems don't usually provide kinesthetic feedback [19]. Most of the haptic devices in the market are still quite expensive.

In this paper, we present the innovative design and implementation of a custom, lightweight, flexible and easy-to-wear haptic glove providing tactile feedback through vibrations, normal indentation, lateral skin stretch as well as kinesthetic feedback by pulling strings attached to fingers. We conduct three experiments evaluating the effectiveness of the glove providing realistic tactile and kinesthetic feedback. The first experiment evaluated realistic feedback for either the softness or hardness of objects. The second experiment investigated the perceived directional information on the user's fingertip, with or without vibration. The last experiment measured users' perception of surface geometry, with or without vibration. Our specific contributions include:

- A custom lightweight, compact and flexible haptic device offering tactile feedback via normal indentation by pressing a moving platform against the fingertip. It provides lateral skin stretch (surface geometry) by applying shear forces to the fingertip and vibration by using an Eccentric Rotating Mass (ERM) motor on each fingertip.

- Our system provides kinesthetic feedback based on strings attached to the glove, pulled to simulate both soft and hard objects. The system controls three servo motors which when actuated, offer the perception of softness or hardness of 3D objects.

- We conduct three experiments on users' perception of softness, hardness, directional information and surface geometry of 3D objects. We determine the accuracy of the perceived

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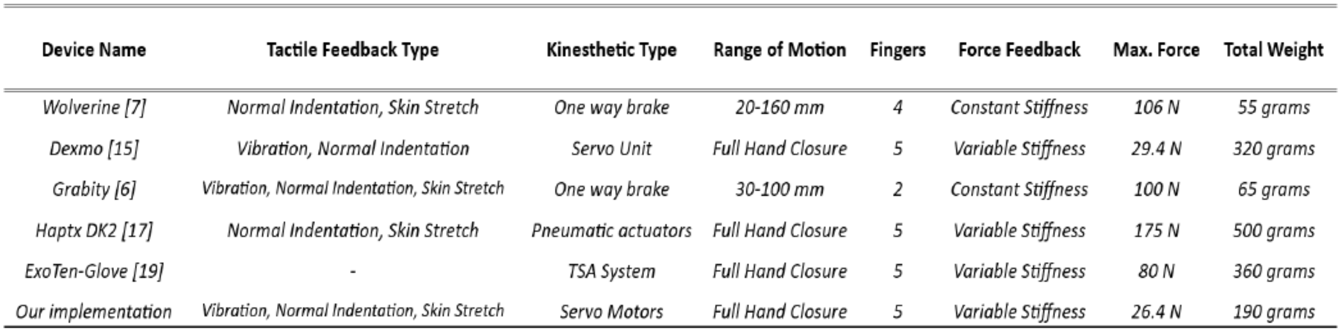

Device Name	Tactile Feedback Type	Kinesthetic Type	Range of Motion	Fingers	Force Feedback	Max. Force	Total Weight
Wolverine [7]	*Normal Indentation, Skin Stretch*	*One way brake*	*20-160 mm*	*4*	*Constant Stiffness*	*106 N*	*55 grams*
Dexmo [15]	*Vibration, Normal Indentation*	*Servo Unit*	*Full Hand Closure*	*5*	*Variable Stiffness*	*29.4 N*	*320 grams*
Grabity [6]	*Vibration, Normal Indentation, Skin Stretch*	*One way brake*	*30-100 mm*	*2*	*Constant Stiffness*	*100 N*	*65 grams*
Haptx DK2 [17]	*Normal Indentation, Skin Stretch*	*Pneumatic actuators*	*Full Hand Closure*	*5*	*Variable Stiffness*	*175 N*	*500 grams*
ExoTen-Glove [19]	-	*TSA System*	*Full Hand Closure*	*5*	*Variable Stiffness*	*80 N*	*360 grams*
Our implementation	*Vibration, Normal Indentation, Skin Stretch*	*Servo Motors*	*Full Hand Closure*	*5*	*Variable Stiffness*	*26.4 N*	*190 grams*

Figure 2: Comparison with other haptic devices

haptic feedback and whether vibrations improve directional information and surface geometry feedback.

2 RELATED WORK

We include an overview of haptic devices (Fig. 2). Early work focused mainly on grounded devices [11], [33]. In cultural heritage, grounded haptic devices were deployed for interaction with 3D artifacts [21], [3]. These devices offered accurate kinesthetic feedback to the user, but, they were heavy and, thus, not wearable [29].

2.1 Dorsal-Based Haptic Devices

Past research has focused on moving the grounding point of the system on top of the hand closer to the actuation point, developing exoskeletons, i.e., a robotic system blocking the hand's movement when there is contact between the virtual hand and a virtual object. Dexmo Glove [15], is a wearable exoskeleton, providing variable kinesthetic feedback, allowing the user to feel the size and shape of any 3D object as well as providing multiple stiffness layers simulation, being wireless with an overall latency of 20-50ms. However, there is no enriched tactile feedback in terms of vibration, normal indentation and lateral skin stretch. Haptx [17], created a haptic feedback glove using microfluidic technology on pneumatic actuators to displace the skin up to 2mm, applying physical pressure to the hand. However, the system requires an air compressor to control the actuators, which makes the interface heavy. An inexpensive haptic device that has the actuation point on top of the hand, provided kinesthetic feedback through an exoskeleton and five servo motors that block its movement when there is collision with a 3D object [34]. Tactile feedback was implemented through fifteen Eccentric Rotating Mass (ERM) motors. However, this implementation was cumbersome and fatiguing. The tactile feedback is provided only through vibrations and the kinesthetic feedback does not offer varied levels of stiffness. A wireless embedded system for hand motion capture integrated an IR pass-filtered camera detecting three IR LEDs attached to a 3D printed base on the glove [10]. An accelerometer/gyroscope for the pitch and roll was added and tactile feedback was communicated through five vibration motors attached to the fingertips. However, this implementation lacked kinesthetic feedback. In our work, kinesthetic feedback is provided by strings instead of an exoskeleton, reducing weight. Also, we provide enriched tactile feedback via vibration, normal indentation and lateral skin stretch, instead of just vibration. We thoroughly evaluate the effectiveness of the glove in providing realistic tactile and kinesthetic feedback.

2.2 Finger-Based Haptic Devices

Another approach to haptic systems is to move the grounding point on top of the fingertip to provide enriched tactile feedback, even closer to the actuation point. An embedded system was developed that offered 3-DoF fingertip cutaneous feedback through a mobile platform providing normal indentation and simulation of the curvature on the fingertip [4]. It provided 1-DoF finger kinesthetic feedback on the proximal and distal interphalangeal finger articulations through an exoskeleton. However, the interface was cumbersome and difficult to use. Origami robotics provided contact and stiffness display via compression and shear; a curvature display via roll and pitch as well as texture via vibration [14]. It was not possible to achieve compression and pitch simultaneously, since compression requires the use of two motors, also designed for one finger only. A wearable cutaneous device for the fingertip provided pressure and skin stretch stimuli by two servo motors and a fabric belt [35]. When the motors rotate in the same direction, shear forces are applied to the finger. When they rotate in a different direction, they provide force to the finger. However, simple passive tangible objects were combined with this device to provide the perception of shape, stiffness and friction. A 3-DoF wearable device for tactile feedback applied normal and tangential shear forces to the fingertip by controlling three cables through three actuators [32] but lacked kinesthetic feedback. Furthermore, a wearable fingertip haptic interface renders virtual shapes and surface features through a moving platform [12], however, the actuators were placed on the finger, making the system cumbersome and difficult to use for long. HapTip, a wearable and compact haptic device provided only 2 DoF shear forces on the fingertip [13]. Our method provides enriched tactile feedback to all fingers instead of just one and does not need passive tangible objects to enhance stimuli perception.

2.3 Handheld Controllers

In [2] the authors designed two handheld controllers providing tactile feedback similar to our implementation. However, they are cumbersome, limiting users' immersion since they grab a controller, lack kinesthetic feedback, and the tactile feedback is limited only to the index finger. A VR controller provided both kinesthetic (rendering continuous softness measure) and enriched tactile feedback (voice coil actuator) to the index finger [8]. This device is heavier than our implementation, not wearable, and limited to one finger. In [6], [7] novel handheld devices were developed, rendering inertia, mass, and tactile feedback in the form of asymmetric skin deformation, and contact forces. Instead, we provide tactile feedback to all fingertips as well as our device being wearable and easy to use in different case scenarios.

2.4 Haptic Feedback Approaches

Recently, the usage of dielectric elastomer actuators has been tested for haptic feedback [22], representing feel-through haptics. It is soft enough so that the user does not perceive when it's turned off. Also, it generates sufficient force when actuated to provide tactile feedback on the fingertip. However, it requires a 500V-1kV power supply to actuate the interface. Chemical haptics deliver topical stimulants to the user's skin [26]. Receptors on the user's skin are

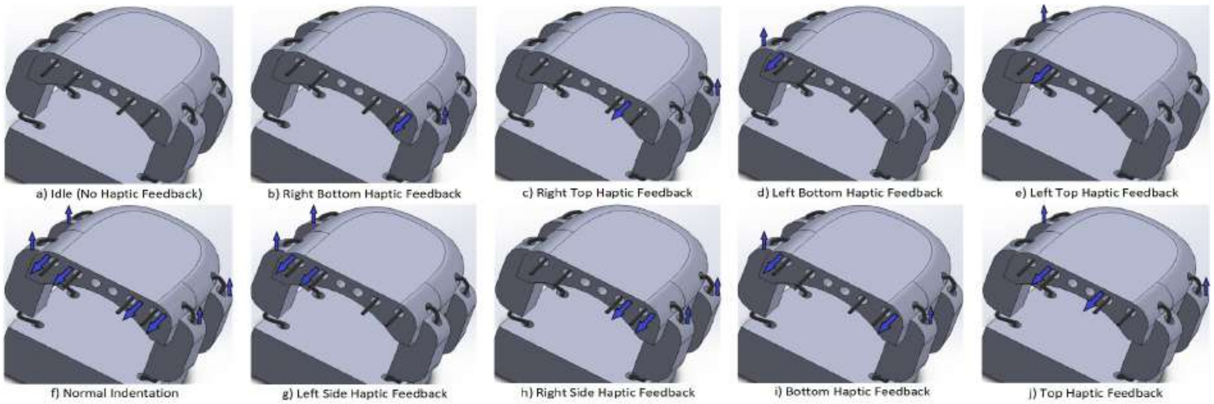
a) Idle (No Haptic Feedback)
b) Right Bottom Haptic Feedback
c) Right Top Haptic Feedback
d) Left Bottom Haptic Feedback
e) Left Top Haptic Feedback
f) Normal Indentation
g) Left Side Haptic Feedback
h) Right Side Haptic Feedback
i) Bottom Haptic Feedback
j) Top Haptic Feedback

Figure 3: The strings that are pulled in each case to simulate location-based tactile feedback to the index finger

chemically triggered, rendering distinct haptic sensations. They use Menthol to simulate the sense of cooling, Capsaicin for warming, Sanshool for tingling and Lidocaine for numbing. However, they do not transition from one sensation to another and sensations do not last for a long time. Our proposed haptic glove requires only 5V to operate. Haptic sensations can last as long as required.

3 IMPLEMENTATION

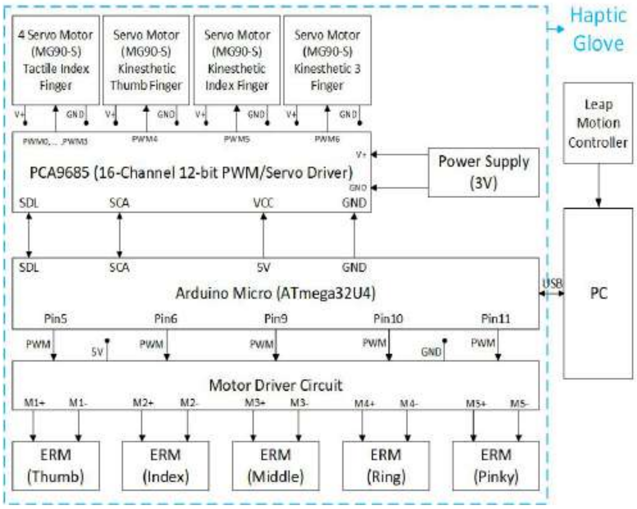

Figure 4: Mechatronic system block diagram with pinout information

3.1 Mechanical Design

We used a total of seven servo motors, each 10.2gr. In order to avoid hindering users' motion and the device being less cumbersome, we placed four of the servo motors around the wrist. These motors are controlling the index finger's moving platform. The rest of the servo motors are placed at the back of the hand and are controlling the kinesthetic feedback through strings. We designed and mounted one 3D-printed part, that weighs 2gr, on each fingernail. We also added four 3D-printed parts that weigh 1gr each, on the middle and proximal phalanx on each finger, except the thumb where we only placed two. The 3D-printed parts have five holes driving the cables and the strings from the motors directly to the fingertips. The 3D-printed parts are designed for an average human finger.

3.2 Tactile Feedback

For enriched tactile feedback, we designed a moving platform for every fingertip placed on the thumb, middle, ring, and pinky fingers, connected with a servo motor through four strings (one on each corner of the moving platform). When the virtual fingers collide with a virtual object, the servo motor rotates and pulls all the strings against the fingertip, providing the user with normal indentation. Additionally, the moving platform that is placed on the index fingertip is connected to four servo motors, each connected to one of the four corners of the moving platform. In this way, we can move it independently from the other corners and in every direction (Fig. 3), providing the user with the following: normal indentation, when all four of the strings are pulled; lateral skin stretch, since the user can feel the directions through the shear forces applied to the fingertip; surface curvature display, since the user can identify round bumps, pointy bumps, and holes. In addition to the moving platform, an ERM vibration motor was added to each platform in order to provide the user with a contact display and perception of the texture of the material when the finger moves on a virtual surface, also keeping the system's weight low. ERM don't require complex circuits adding weight (H-Bridge), being power-efficient since they don't require a continuous flow of a current to maintain the motion. The ERM motors used in this work have a start current draw of 85mA and an operating current draw of 75mA, which is greater than the output current from each pin in Arduino (up to 40mA). Thus, a driver circuit is required to overpass this limitation. The circuit contains an N-channel MOSFET because it works better with 2V and higher (higher Vgs gate turn on-voltage). Also, it requires a Schottky diode to protect the MOSFET against voltage spikes from coils, a pull-down resistor to keep the MOSFET entirely off and an EMI suppression capacitor to reduce the high-frequency electromagnetic noise generated by the motor. This circuit is developed for each servo motor and placed on a custom PCB.

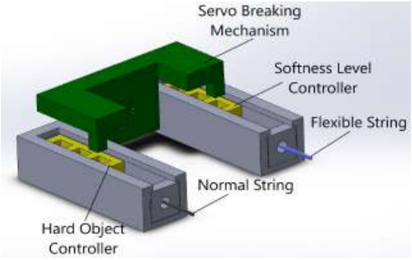

Figure 5: Kinesthetic feedback implementation

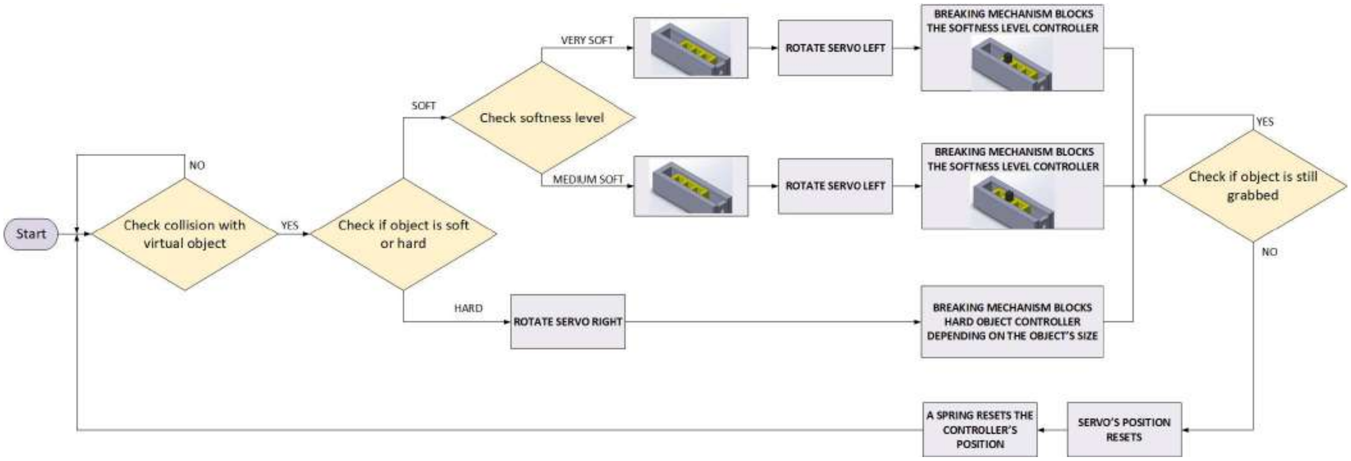

Figure 6: Flowchart of the kinesthetic feedback

3.3 Kinesthetic Feedback

When in contact with a virtual object, the movement of each finger is stopped in order to provide kinesthetic feedback to the user. Our haptic glove utilizes strings attached to a 3D-printed mechanism controlled by a servo motor. Three servo motors are used for kinesthetic feedback, for the thumb, index finger, and one for the remaining three fingers. We render three fingers using one actuator so as to minimize weight. When the user interacts with a 3D object, a method checks whether the object is soft or hard. If soft, it checks the level of its softness. Then, the servo motor rotates the servo-breaking mechanism either left to block the softness level controller or right to block the hard object controller. The softness level controller is connected with the fingers through a flexible string that can stretch and simulate the elasticity of soft objects in two levels. Softer objects have a smaller collider, thus the hand grip closes more to collide with them. The hard object controller is connected with the fingers through a normal string and the breaking mechanism blocks the controller depending on the object's size. The 3D-printed blocks (2cm x 2cm x 3cm), where the hard object controller and the softness level controller move, withstands approx. 26.4 N of force before breaking under tension. The tension in the strings is 196.2 N effectively limiting the user's finger movement providing resistance and kinesthetic feedback. In order to drive the servo motors, the Arduino offers the Servo library. However, each servo will consume a pin and an amount of Arduino processing power. In order to address this, a PCA9685 16-Channel 12-bit PWM/Servo Driver is employed for driving these motors. The PCA9685 is able to drive up to sixteen servos over I2C with only two pins and with the onboard PWM controller this will occur simultaneously.

4 USER STUDIES

We conduct user experiments to evaluate haptic feedback by assessing the perception of object softness or hardness as well as lateral skin stretch on the fingertip and user recognition of surface geometry. We used a 27" Samsung CJG50 monitor (2560 x 1440, 144 Hz) connected to a PC (desktop, CPU AMD Ryzen 7-3700X, 16 GB RAM, single Radeon GPU RX-5700XT) and a Leap Motion Controller to track the user's hand and fingers. 18 participants took part, e.g. 7 females, average age 26.67, SD 2.68, with normal or corrected-to-normal vision. Participants were placed in front of the screen as seen in Fig. 1a, wore the haptic glove and interacted with 3D objects in order to get familiar with the Leap Motion Controller's tracking. They wore headphones for isolation. Our glove was designed for the 90th percentile of hand dimensions. It was worn on the left hand but a new glove could easily be mirrored for the right hand. Then, the experiment sequence was initiated. The average time to finish the three experiments was around 27.5 minutes.

4.1 Experiment 1: Softness/Hardness Perception

The experiment investigated the perception of either the softness or hardness of 3D objects. Participants were presented with pairs of spheres. Randomly, the two spheres had either 0, 1, or 2 as an attribute value, representing soft, medium soft, and hard objects respectively. Pairs of all levels were presented three times and participants were given 10 seconds to manipulate each sphere. After showing each pair to participants, they reported whether the first or the second sphere was perceived as softer, or whether the two were perceived as similar. For each pair of spheres, we recorded the answers provided. In order to collect the data, we used a user interface with three buttons. Following the presentation of the two spheres, the user was asked to report, by moving an on-screen cursor, which sphere was softer or whether they were the same.

4.2 Experiment 2: Lateral Skin Stretch Perception

Each participant was presented with stimuli from the moving platform. By pulling one or more of the four strings attached to the moving platform, participants felt specific directional information. Each direction was presented 3 times and in random order. After the 3 seconds passed from the exposure to the stimuli, participants were presented with 8 buttons (one for each direction) and reported which one of the 8 they felt. This process was repeated with the addition of vibration feedback to participants' index fingertips. We recorded participants' answers. We used a similar user interface as in Experiment 1, with 8 buttons (one for each direction) to collect user data. The user interface popped up after each sequence ended, asking participants which direction they felt on their fingertips.

4.3 Experiment 3: Surface Geometry Perception

Participants were instructed to move their hands from left to right through a black box. When the participants' index finger was inside the box, they were exposed to stimuli from the moving platform by pulling one or more of the four strings attached to it. The platform's movement simulated four surface geometries: a round bump, a triangle ramp, a round ramp, and a triangle bump. After 3 seconds of stimuli presentation, participants selected which one they felt. Then, this process was repeated with the addition of vibration feedback to participants' index fingertips. After every stimulus, participants were presented with a user interface containing 4 buttons. The answers provided by the participants were recorded.

5 RESULTS AND DISCUSSION

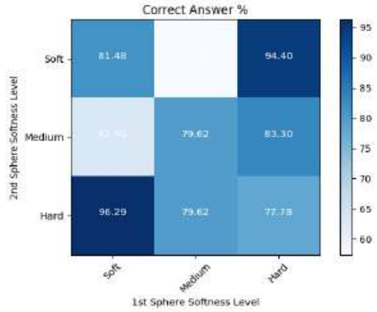

Figure 7: The percentage of correct answers on each combination

The results from the softness/hardness perception experiment (Experiment 1) indicated higher accuracy when the user was required to distinguish between a soft and a hard sphere, with success rates of 96,29% and 94.4% respectively (Fig. 7). The success rate significantly decreased to 62.9% and 57.4% when the softness on the two spheres was medium soft and soft. The results suggest that the users found it difficult to detect subtle differences in softness.

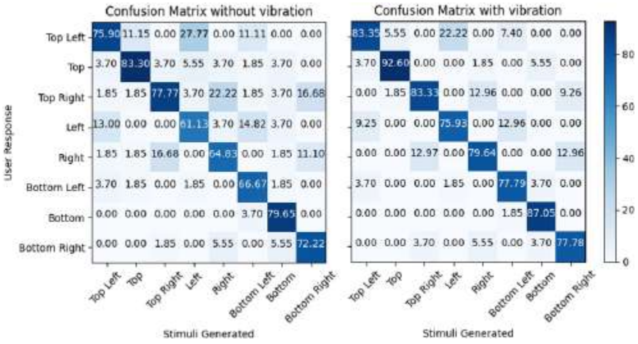

Figure 8: Confusion matrices of 2nd exp. with and without vibration on fingertip

As shown in Fig. 8, results from the lateral skin stretch experiment (Experiment 2) indicated that participants identified the orientation of the platform with success rates of over 61.13% depending on the specific orientation. With the addition of vibration on the fingertip, the success rates increased above 75.93%. These results suggest that the participant's ability to distinguish the orientation of the platform was enhanced by adding vibration to the fingertip.

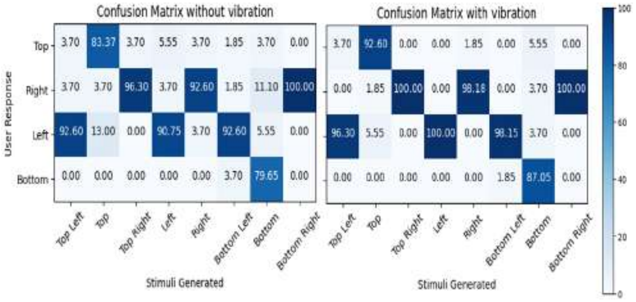

Figure 9: Confusion matrices of the simplified orientations with and without vibration

In Fig. 9, we condensed the results by grouping them into the following categories: top left, left, and bottom left orientation to left; top right, right, and bottom right orientation to right; top orientation is kept as top; bottom orientation is kept as bottom. Grouping the 8 orientations in four categories indicated that participants distinguished the main orientation of the platform with success rates above 87.05% (with vibration) and 79.65% (without vibration). Thus, the users identified the main orientation of the platform (top, left, right, bottom), but found it more challenging to recognize the specific orientation (corners). The addition of vibration on the fingertip improves the results.

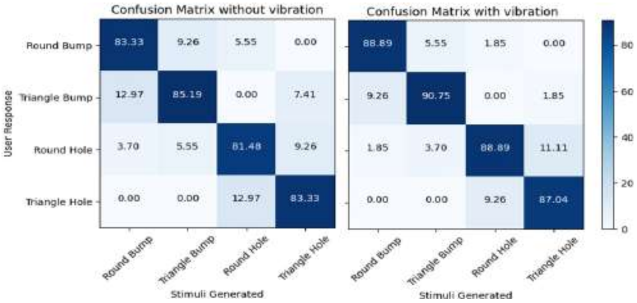

Figure 10: Confusion matrices of the 3rd exp. with and without vibration on fingertip

As shown in Fig. 10, the results from experiment 3 indicated that participants were able to distinguish the geometry of the surface with success rates above 81.48% (without vibration) and 87.04% (with vibration). Participants identified minor differences in the geometry, which was improved with the addition of vibrations.

6 DISCUSSION AND CONCLUSION

We propose an innovative wearable haptic feedback device that provides tactile feedback in the form of vibration, normal indentation and surface geometry perception. Our implementation utilizes four servo motors, connected to a moving platform placed on the fingertip and can move the platform in eight directions. Unlike past systems, the haptic glove proposed is lightweight and compact. The system also provides kinesthetic feedback simulating the softness of objects in two distinct levels and the interaction with various-sized solid objects. We performed three formal experiments to evaluate users' perception of either softness or hardness of objects, directional information and surface geometry. Our analysis shows that the addition of vibration in the second and third experiment improved the perception of directional information and surface geometry. The results from the first experiment revealed that users find it hard to distinguish minor differences between soft and slightly harder or medium soft objects. However, the success rate increased when the differences in softness were more distinct. Participants without prior experience with the Leap Motion Controller took extra time to practice, but stated that the haptic glove was light and easy to wear. After successfully completing the experiments, they reported that the sensory feedback was unique and that they felt touching both soft and hard objects. They were amazed by geometry perception, able to feel differently shaped objects. Transparently creating the illusion of touch, pressure and other tactile sensations at high fidelity, without being disrupted by worn hardware, is still an open research question. In the future, we aim for a wireless device without cables. A new tracking system will replace the Leap Motion Controller for independence from external tracking devices. ERM motors present a single vibration stimulus, resulting in limited vibration stimulation, thus we will employ Linear Resonant Actuators(LRA). As in most prototype haptic devices, a limitation of the proposed haptic device is that it does not accommodate varied hand and finger sizes. This has to be accounted by producing prototype devices in varied sizes. Although our implementation provides accurate feedback on either the soft or hard features of 3D objects, it will be redesigned using a servo motor controlling softness independently from the one used for hardness, in order to be perceptually accurate even when very subtle differences in softness levels are present.

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REFERENCES

[1] Q.-Z. Ang, B. Horan, and S. Nahavandi. Multipoint haptic mediator interface for robotic teleoperation. *IEEE Syst. Journ.*, 9(1):86–97, 2015.

[2] H. Benko, C. Holz, M. Sinclair, and E. Ofek. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. UIST '16, p. 717–728. ACM, 2016.

[3] S. Ceccacci, A. Generosi, A. Leopardi, M. Mengoni, Mandorli, and Ferruccio. The role of haptic feedback and gamification in virtual museum systems. *J. Comput. Cult. Herit.*, 14(3), 2021.

[4] F. Chinello, M. Malvezzi, D. Prattichizzo, and C. Pacchierotti. A modular wearable finger interface for cutaneous and kinesthetic interaction: Control and evaluation. *IEEE Trans. on Industrial Electronics*, 67(1):706–716, 2020.

[5] F. Chinello, C. Pacchierotti, M. Malvezzi, and D. Prattichizzo. A three revolute-revolute-spherical wearable fingertip cutaneous device for stiffness rendering. *IEEE ToH*, 11(1):39–50, 2018.

[6] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. UIST '17, p. 119–130. ACM, 2017.

[7] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer. Wolverine: A wearable haptic interface for grasping in virtual reality. In *2016 IEEE/RSJ Inter. Conf. on Intelligent Robots and Systems (IROS)*, pp. 986–993, 2016.

[8] I. Choi, E. Ofek, H. Benko, M. Sinclair, and C. Holz. Claw: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality. CHI '18, p. 1–13. ACM, 2018.

[9] D. D'Auria, F. Persia, and B. Siciliano. A low-cost haptic system for wrist rehabilitation. In *2015 IEEE Inter. Conf. on Information Reuse and Integration*, pp. 491–495, 2015.

[10] M. Efraimidis and K. Mania. Wireless embedded system on a glove for hand motion capture and tactile feedback in 3d environments. In *SIGGRAPH Asia 2020 Posters*, SA '20. ACM, 2020.

[11] Hapticvr, 2023. http://www.fundamentalvr.com.

[12] M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. In *2016 IEEE Haptics Symp. (HAPTICS)*, pp. 140–146, 2016.

[13] A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. Lécuyer. Haptip: Displaying haptic shear forces at the fingertips for multi-finger interaction in virtual environments. *Front. in ICT*, 3, 2016.

[14] F. H. Giraud, S. Joshi, and J. Paik. Haptigami: A fingertip haptic interface with vibrotactile and 3-dof cutaneous force feedback. *IEEE ToH*, 15(1):131–141, 2022.

[15] X. Gu, Y. Zhang, W. Sun, Y. Bian, D. Zhou, and P. O. Kristensson. Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in vr. CHI '16, p. 1991–1995. ACM, 2016.

[16] A. Gupta and M. O'Malley. Design of a haptic arm exoskeleton for training and rehabilitation. *IEEE/ASME Trans. on Mechatronics*, 11(3):280–289, 2006.

[17] Haptic gloves dk2, 2018. http://www.haptx.com.

[18] R. Hinchet, V. Vechev, H. Shea, and O. Hilliges. Dextres: Wearable haptic feedback for grasping in vr via a thin form-factor electrostatic brake. UIST '18, p. 901–912. ACM, 2018.

[19] M. Hosseini, A. Sengül, Y. Pane, J. De Schutter, and H. Bruyninck. Exoten-glove: A force-feedback haptic glove based on twisted string actuation system. In *2018 27th IEEE Inter. Symp. on Robot and Human Interactive Communication (RO-MAN)*, pp. 320–327, 2018.

[20] J. Iqbal, N. Tsagarakis, and D. Caldwell. Four-fingered lightweight exoskeleton robotic device accommodating different hand sizes. *Electr. Lett.*, 51(12):888–890, 2015.

[21] M. H. Jamil, P. S. Annor, J. Sharfman, R. Parthesius, I. Garachon, and M. Eid. The role of haptics in digital archaeology and heritage recording processes. In *2018 IEEE Inter. Symp. on Haptic, Audio and Visual Environments and Games (HAVE)*, pp. 1–6, 2018.

[22] X. Ji, X. Liu, V. Cacucciolo, Y. Civet, A. El Haitami, S. Cantin, Y. Perriard, and H. Shea. Untethered feel-through haptics using 18-µm thick dielectric elastomer actuators. *Adv. Funct. Mater.*, 31(39):2006639, 2021.

[23] J. Kreimeier, S. Hammer, D. Friedmann, P. Karg, C. Bühner, L. Bankel, and T. Götzelmann. Evaluation of different types of haptic feedback influencing the task-based presence and performance in virtual reality. PETRA '19, p. 289–298. ACM, 2019.

[24] S. Krumpen, R. Klein, and M. Weinmann. Towards tangible cultural heritage experiences—enriching vr-based object inspection with haptic feedback. *J. Comput. Cult. Herit.*, 15(1), 2021.

[25] D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli. A 3-rsr haptic wearable device for rendering fingertip contact forces. *IEEE ToH*, 10(3):305–316, 2017.

[26] J. Lu, Z. Liu, J. Brooks, and P. Lopes. Chemical haptics: Rendering haptic sensations via topical stimulants. UIST '21, p. 239–257. ACM, 2021.

[27] J. Ma, L. Sindorf, I. Liao, and J. Frazier. Using a tangible versus a multi-touch graphical user interface to support data exploration at a museum exhibit. TEI '15, p. 33–40. ACM, 2015.

[28] S. Nisar, M. O. Martinez, T. Endo, F. Matsuno, and A. M. Okamura. Effects of different hand-grounding locations on haptic performance with a wearable kinesthetic haptic device. *IEEE Robotics and Automation Letters*, 4(2):351–358, 2019.

[29] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo. Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives. *IEEE ToH*, 10(4):580–600, 2017.

[30] C. Pacchierotti, A. Tirmizi, G. Bianchini, and D. Prattichizzo. Enhancing the performance of passive teleoperation systems via cutaneous feedback. *IEEE ToH*, 8(4):397–409, 2015.

[31] R. M. Pierce, E. A. Fedalei, and K. J. Kuchenbecker. A wearable device for controlling a robot gripper with fingertip contact, pressure, vibrotactile, and grip force feedback. In *2014 IEEE Haptics Symp. (HAPTICS)*, pp. 19–25, 2014.

[32] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi. Towards wearability in fingertip haptics: A 3-dof wearable device for cutaneous force feedback. *IEEE ToH*, 6(4):506–516, 2013.

[33] Optimo arm, 2023. http://www.roboligent.com.

[34] M. Roumeliotis and K. Mania. Development of a wearable embedded system providing tactile and kinesthetic haptics feedback for 3d interactive applications. In *SIGGRAPH Asia 2021 Posters*, SA '21 Posters. ACM, 2021.

[35] S. V. Salazar, C. Pacchierotti, X. de Tinguy, A. Maciel, and M. Marchal. Altering the stiffness, friction, and shape perception of tangible objects in virtual reality using wearable haptics. *IEEE ToH*, 13(1):167–174, 2020.

[36] S. B. Schorr and A. M. Okamura. Fingertip tactile devices for virtual object manipulation and exploration. CHI '17, p. 3115–3119. ACM, 2017.

[37] M. Solazzi, A. Frisoli, and M. Bergamasco. Design of a novel finger haptic interface for contact and orientation display. In *2010 IEEE Haptics Symp.*, pp. 129–132, 2010.

[38] K. Tadano, M. Akai, K. Kadota, and K. Kawashima. Development of grip amplified glove using bi-articular mechanism with pneumatic artificial rubber muscle. ICRA '10, pp. 2363–2368, 2010.

[39] E. Whitmire, H. Benko, C. Holz, E. Ofek, and M. Sinclair. Haptic

revolver: Touch, shear, texture, and shape rendering on a reconfigurable virtual reality controller. CHI '18, p. 1–12. ACM, 2018.