Can A Vibrotactile Stimulation On Fingertips Make An Illusion Of Elbow Joint Movement?

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Dinmukhammed Mukashev, Adilzhan Adilkhanov, *Student Members, IEEE,*
Zhanat Kappassov, *Member, IEEE*

***Abstract*— With the proliferation of haptic interfaces, the vibrotactile capabilities are accessible to a substantial number of end-users allowing a more realistic experience with Virtual Reality. Currently, the primary use of this vibrotactile feedback is to provide additional support to visual interaction via prehensile object manipulation using fingers. Nevertheless, haptic stimuli can be also applied for non-prehensile interaction that involves movements of the elbow joint. In this paper, we have designed and evaluated a vibrotactile device to investigate the effect of haptic stimuli, applied onto the fingertips, on a sensation of elbow displacements. The vision-driven displacement produced by the pseudo-haptics effect is then amplified by the vibrotactile stimuli. The experimental platform consists of a voice-coil actuator and a force sensor for generating mechanical vibrations at fingertips. The efficacy of the approach was validated in experiments with human subjects. The results show that the combination of pseudo-haptic and haptic illusion effects can be used to render various soft and rigid virtual objects.**

Fig. 1. Experimental procedure: a user wearing VR goggles is using the haptic device to perform the task (seen on the screen).

I. Introduction

Virtual Reality (VR) applications have been experiencing an increased interest in recent years. Research studies in human perception revealed that a deeper dive into the Virtual Environment (VE) is possible through the conjunction of AR/VR and haptic feedback as it reduces cognitive load and increases performance [1]. According to Hayward et al. [2], the word "haptics" refers to the capability to sense a natural or synthetic mechanical environment through touch. Our tactile sensation is mediated by a combination of receptors inside our skin. In general, human haptic perception consists of two: kinesthetic haptic feedback and cutaneous (tactile) haptic feedback. Kinesthetic feedback refers to the sense of position and motion of one's body state mediated by a variety of receptors located in the skin, joints, skeletal muscles and tendons [2]. Cutaneous feedback is related to the stimuli detected by low threshold mechanoreceptors under the skin within the contact area [3].

In this connection, multiple new paradigms in VR devices have surged in recent years. They include wearable and non-wearable haptic devices used for the interactions with the VE. Haptic devices are used to engage these feedbacks and make users have the feeling of touch (provide haptic illusions). Devices addressed to stimulate kinesthesia are typically grounded, bulky, mechanically complex, expensive and have a limited workspace. Traditionally, kinesthetic devices are able to provide clear force or torque to move a user's hand or resist motion [4]. The most popular commercial examples are Phantom (Sensable Technologies, USA) and Omega (Force Dimension, Switzerland). They are widely used in industry and medicine for teleoperation tasks and other tool-based applications (e.g. manipulator hand, dental drill) [5].

It has been shown that to some extent it is possible to compensate for a lack of kinesthesia with the modulated cutaneous force technique, without significant performance degradation [6]. Cutaneous feedback can be displayed by mobile, lightweight, compact devices that can be wearable and mounted on a user's body. Specifically, fingertips are one of the most stimulated areas of the human body as they are involved in almost all our tactile interaction with the environment. Fingerpads rich with mechanoreceptors [7] are being mostly stimulated through cutaneous feedback to give sensations of surface softness, curvature, edges, and texture [8], and object's weight [9].

In recent human perception studies, it was shown that fluctuations, resembling the mechanical response of granular solids, provoke a sensation of limb displacement even during pressing with a finger on a stiff surface [10]. The mechanical response of granular solids was replicated using the haptic device described in our previous work [11]. The developed device provoked the sensation of index finger and thumb movements during a tip grasp of the stiff device of an object seen in an HMD. In this work, we aim in table-top haptic feedback device that excites the feeling of elbow movement

The authors are with the Department of Robotics and Mechatronics, School of Engineering and Digital Sciences, Nazarbayev University, Nur-Sultan, Kazakhstan.

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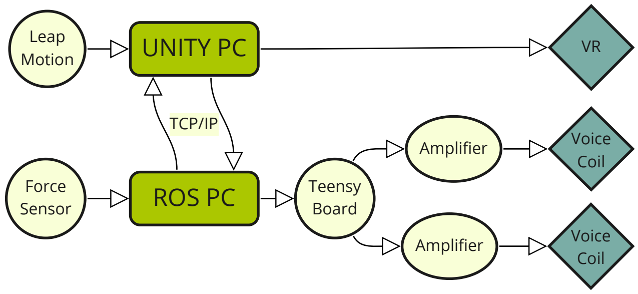

Fig. 2. Schematic explanation of setup

by combining pseudo-haptics and vibrotactile feedback. The contribution that this research intends to make is discovering to what extent the vibrational stimulation can cause a haptic illusion of kinesthesia, i.e. elbow joint movement. Several studies [12], [13] were conducted to create a vice-versa simulation (e.g. illusion of fingertips perception while simulating wrist or forearm).

The newly introduced device shares the key hardware design and stimuli actuation principles with the one in [11]. The changes in the system and the VE architecture are firstly introduced in the following section. Afterward, the experimental procedure with human subjects is presented in Section IV. The recorded data were processed with the necessary statistical tools such as one-way and two-way analysis of variance (ANOVA). We conclude the work by discussing results, arisen issues, and future improvements.

II. Experimental Platform

The setup consists of three main parts: hardware including actuators and force sensors, software for obtaining data from the sensor, and a virtual reality interface.

A. Hardware

In order to produce vibrotactile feedback in response to a user's applied force, we integrated the six-axis force/torque sensor (Weiss KMS 40-C, Weiss Robotics, Germany). For our application, the sensor was securely attached to a basis (ThorLabs optical table) and was pressed only in one direction (vertically - Z-axis). The sensor has a sampling rate of 500 Hz and 16 bit resolution which is enough to modulate proper vibrations [4]. The sensor is capable of operation up to 120 N. It is factory calibrated and provides the data directly in the SI unit. The rest of the hardware was mounted on top of the force sensor as it is shown in Figure 3.

The obtained data from the force sensor was handled by the Robot Operating System (ROS) for the further modulation of vibrations and the use by VR application. In ROS, we have employed the open-source package by Lorenz Halt [1]. Further, this data is sent to the processing board (Teensy USB Board, Version 3.6, PJRS, USA) and Unity PC.

Teensy board with two digital-to-analog converting (DAC) ports was used to obtain the data from the force sensor (through a special Arduino package called 'rosserial'), and

[1]https://github.com/ipa320/weiss_kms40

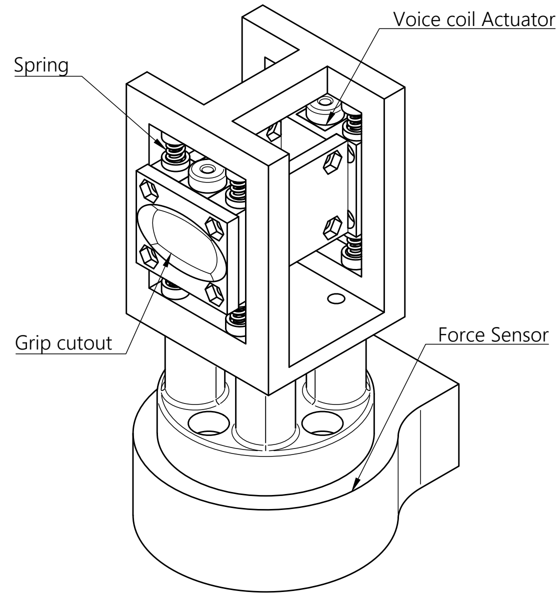

Fig. 3. Wireframe view of device in full assemble

to generate proper vibrations utilizing linear voice-coil actuators (Tactuator MMXC series, Tactile Labs, Germany). The communication between ROS PC and the board was held through the USB serial port.

The pair of the voice coil actuators were used to deliver tactile cues to a user's fingerpads. As it can be seen from Figure 3, two actuators were placed vertically on the sides of the device. Such structure of the device was designed to mimic a grip of rod or stick (as explained in Section II-B) with thumb and index finger. The analog signal from the Teensy board to the actuators was amplified by the class-D Type Amplifier (Adafruit Mono 2.5W Class D Audio Amplifier - PAM8302, Adafruit Industries, USA). The bandwidth range of vibration is from 90 Hz to 1000 Hz what allows to have a choice of different vibration modes.

The generated vibrations are spread well through the solid objects. Thus, four springs per motor were used to avoid vibration suppression and convey all tactile sensations to the fingertips (Figure 3). Each spring has a constant of $k = 200\ N/m$ what is enough to keep the actuators stationary in relation to the device's enclosing structure. Indeed, the shift under the maximum vertical load of 16.5 N was less than 1 mm. This shift can be neglected as it is quite less than the displacement of the hand, rendered in VR. To isolate and hold in place the voice coil, four springs were used for each motor by two from each side which adds up to a total of 8 springs for two motors.

The enclosing structure of the device was 3D printed on Ultimaker S5 (Ultimaker, Netherlands) with Polylactic acid (PLA) plastic filament. It has cutouts for index and thumb fingers (Figure 3) on the sides for better grip. To avoid the shift of two fingers towards each other, the 3D printed limiter part was mounted between two actuators.

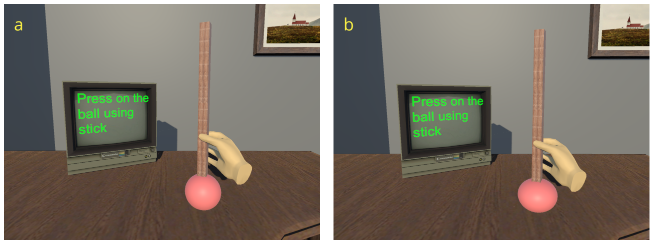

Fig. 4. Pciture (a) view from the VE. Picture (b) same view with squeezed ball

B. Virtual Reality

The VR goggles (Oculus Rift, Oculus, USA) were used as a device to show the VE environment (Figure 4) to testee (Figure 1). For one part of the experiment, Leap Motion Controller (Ultraleap, USA) was used to simulate the real hand in the virtual environment. The environment was created using the Unity Real-Time Development Platform (Version 2019.1.7f1). All models (i.e monitor, hand, table, etc.) were loaded from Unity's Assets store which is available for any registered user. The Virtual environment contains an interior element to give the user sense of scale.

The Leap Motion Controller was used in one of the parts of the experiment. On the hand model given by lip motion, the virtual stick was attached. It had a *collider* (Invisible mesh of object shape used to simulate the physical collision events) component which interacts with a sphere's *collider*. Thus, the squeeze effect from the real hand movements was implemented.

III. Methodology

A signal from the Teensy board was sent to motors as sinusoidal function v where the component R was varied depending on the force rate, while values A, ϕ were constants:

$$v = A \cdot sin(\phi \cdot R); \tag{1}$$

The rate of force (R) was measured as a derivative of the applied force. Further, the force rate was normalized and filtered. Thus,

$$R = 1 - R_{norm} \tag{2}$$

Where R_{norm} is a normalized rate. It is reverted since the number of rate increases, it should contribute to the increased frequency and because the ϕ is a number less than 1. The multiplied number should be larger to increase the resulting frequency as the force rate increases.

ϕ was chosen to be 0.1 or 0.5 for different parts of experiments with a combination of different sampling rates from the sensor: $dt = 10, 5, 2$ (where it corresponds to sample every dt milliseconds). Also, the upper force limits were set to $6.5N$, $11.5N$, and $16.5N$. Those three values were chosen to have an obvious separation in travel distances. As for vibrations, the same limits were set in the VE for the travel limit of the bar.

As the force reaches upper or lower force limits, the output v sets to 0. Similarly, upper and lower thresholds were set for the normalized force rate of change: lower limit 0.01 and upper limit 0.3.

For the stick displacement and ball deformation:

$$d = F/(10 \cdot c) \tag{3}$$

the value of coefficient c was left as variable to be able to adjust and fine tune the stick and ball movements. However, for the experiment it was set $c = 10$ for all modes and only thresholds for the force F were left as control of the bar travel.

Also, the ball shape control was implemented similarly. The Z component of the scale of the ball was decreased by the value d while the X and Y components increased. Also, the ball was shifted by $d/2$ along the Z-axis to compensate for the squeeze (it was scaled from both sides with respect to the middle of the ball) and stay on the table.

IV. Perceptual Evaluation

The Collaborative Institutional Training Initiative (CITI) Program's Health Information Privacy and Security course was completed by the authors prior to the experiment. After that, the protocol of the experiment (NU-IREC 357/06012021) was approved by the Institutional Research Ethics Committee (IREC) of Nazarbayev University (NU).

A. Participants

There were ten volunteers involved in the experiments. Subjects (7 male and 3 female) were chosen randomly regardless of their familiarity with technologies in the field of this research. None of the participants reported any physical injuries or mental disorders, specifically in visual or haptic perception abilities. Instructions were provided to each participant in written and verbal forms before the procedure started. Subjects were asked to remove gloves, watches, bracelets, and jewelry if any as it may cause discomfort during the experiment.

B. Procedure

Before the start of measurements, subjects were asked to put on the Oculus Rift VR HMD and try to squeeze the virtual ball without the haptic device, e.g. move the hand in front of the Leap Motion Controller (Ultraleap Co., UK). As the motion tracking sensor allows a free movement, this step was needed to give the subjects an opportunity to feel the real movement of the hand during the ball squeeze task. After several trials, participants responded a value of distance perceived keeping in mind diameter of the virtual ball.

Following, participants were asked to put on headphones that produce white noise at the volume that allows to eliminate sound from the vibromotors. After that, a trained instructor helped to place their forearm on a special support and hold the device with their index finger and thumb (Fig. 1). According to the instruction, participants had to push on the virtual ball with a bottom end of the virtual stick five times. The counter (from 5 to 0) was displayed on the screen of the virtual monitor in order to make a user's aware of his/her progress. The value of the counter

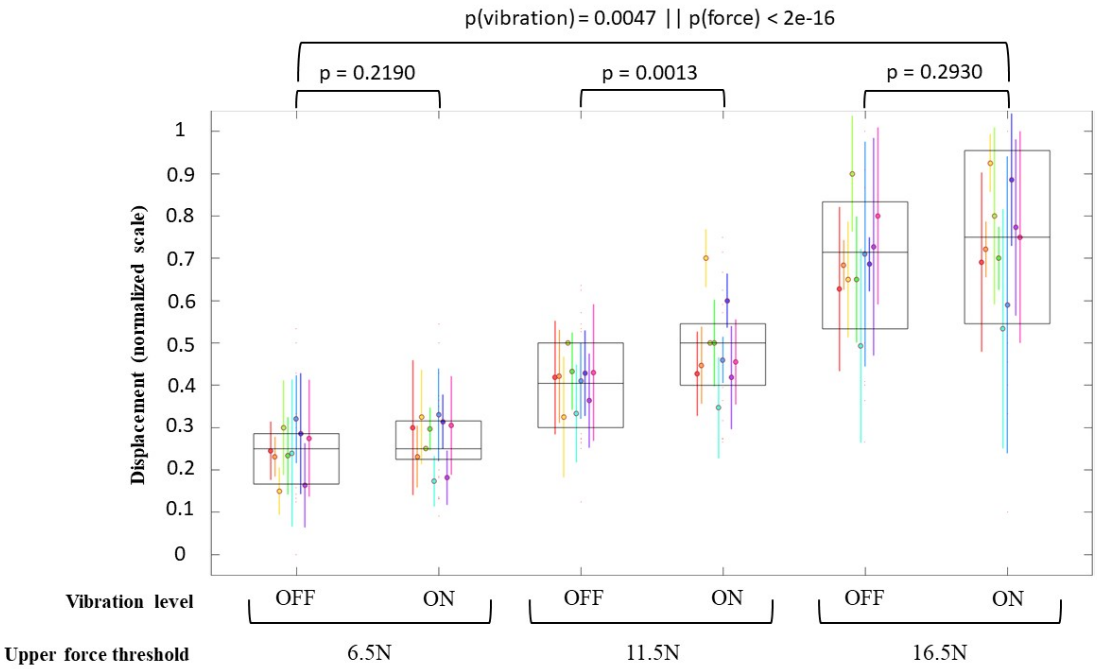

Fig. 5. The result of the experiment with 10 subjects (each subject is indicated with different color). The colored vertical bars and dots denote the average and standard deviation for each subject on each operational mode, respectively. The average and standard deviation per operational mode are shown with boxes. The result of ANOVA test (p-value) is displayed on the top of the figure.

changes every time a user reaches the minimal applied force threshold. When the counter drops to zero, there is shown a text ”Report the number”. This means that a participant has to tell verbally the average hand's displacement value perceived during these five squeezes. After that, the device's operational mode changes, the counter showing ”5” appears on the virtual screen, and a participant has to repeat the task. Overall, there were 5 rounds of 13 operational modes. The modes were shuffled differently in these five rounds. The time required to complete the task is around 10 minutes.

C. Statistical Methods

The aim of this study is to evaluate how the vibrotactile stimulation elicited by our haptic device enlarges the visual perception of limb displacement. After the experimental data collection, the perceived displacement values of each testee were normalized by dividing all the raw values by the given testee's maximum responded value. Despite that the all participants were provided with dimensions of the virtual ball and had the opportunity to feel real movement of the hand, the responded values significantly differed from one subject to another. Thereby, the maximum value is 1, and the minimum is 0 as it is depicted on Figure 5. Only six operational modes were included into further analysis because there were no significant difference between the resultant effect of 3 vibrational levels ($\phi = 0.1, 0.1, 0.5$ with $dt = 10, 5, 2$ respectively). Therefore, only ($\phi = 0.1$ and $dt = 10$) vibrational coefficient was considered.

As it can be seen in Figure 5, the perceived movement of the elbow joint depends more on the applied force threshold - the higher the applied force, the more the stick flattens the ball. Considering the sizes of the objects, such deformation is easily visually detectable by users. Therefore, the difference in responses between different is more noticeable than than the difference within force factor groups. However, there is an effect of vibrotactile stimulation as the perceived displacement due to combination of visual and haptic stimuli is slightly greater than those without vibrations.

Table 1. One-Way ANOVA

Factor	Force threshold	F value	p value
vibration	6.5N	1.532	0.219
vibration	11.5N	10.91	0.00133
vibration	16.5N	1.119	0.293

Table 2. Two-Way ANOVA

Factor	F value	p value
vibration	8.101	0.00473
force threshold	229.385	¡2e-16

In order to validate the significance of our results, we have performed ANOVA tests. Firstly, we decided to verify the effect of vibration within each of the three upper force threshold pairs. The pairwise one-way ANOVA (Table 1) was taken for the records by the factor of vibration level (e.g. enabled vibrations - ”ON” and disabled vibrations - ”OFF”). The difference of data in the first pair (from the left on Fig. 5) is statistically insignificant (‘ ’: p = 0.219), and the same for the third pair (’ ’: p = 0.2930). However, for the pair of force threshold equal to 11.5 N the difference of data is meaningful (’**’: p = 0.00133).

Further, in order to check the effect of each of the two parameters - vibration level and upper force threshold ($F_{th} =$

$6.5\ N$; $F_{th} = 11.5\ N$; $F_{th} = 16.5\ N$) - we performed the two-way ANOVA test for the records. According to Table 2, if considering the combination of the two factors, it makes the result statistically significant with low probability of getting these records by chance (p value for the vibration factor = 0.00473 '**'; p value for the force threshold factor is less than 2e-16 '***').

D. Results

Compare to the effect on illusory finger displacements reported in figure ten in [11], a similar vibrotactile stimulation has less effect on perception of illusory elbow displacements (Table IV-C).

There are multiple reasons that could cause this discrepancy. First, the size of the ball in this work was larger than in the former one, which inclined the subjects to rely more in the visual cues (pseudo-haptics) rather than on the haptic cues. Second, according to human cortical homunculus, the number of tactile receptors varies dramatically in different parts of a human body and it is much higher in the fingers and palm side than in the elbow. Finally, the applied haptic stimuli may have a stronger effect in the middle band of the force range: the reports of the participants analyzed with one-way *anova()* reveal that for the lower (6.5 N) and higher (16.5 N) force threshold, the results are statistically insignificant and, therefore, the vibrotactile stimulation does not amplify the perception of the elbow displacement seen in HMD; in contrast, in the middle range of muscular efforts (force threshold of 11.5 N), there is a dependence on perceived elbow displacements: a larger limb displacement is sensed when the vibrotactile stimuli is applied.

In order to investigate this issue, we conducted experiments without the visual feedback (eyes closes). Similar to the resulted reported in [10] and in [11], a longer stimulation time interval (i.e. a higher force threshold) causes a sensation of a larger limb displacements. This fact indicates that the size of the ball was big enough to strengthen the visual cues and, thus, the pseudo-haptic effect.

In overall, a two-way *anova()* (Table IV-C) demonstrates that the combination of visual and vibrotactile stimuli causes a sensation of elbow displacement perceived through VR application.

V. Conclusion

In this paper, we extended our previous work [11] for non-prehensile object manipulation in the VE. Specifically, we described the capability of our new table-top haptic device to enhance the quality of perceived haptic clues representing the softness of an object being poked via a grasped object in the VE seen in a HMD.

Empirical results demonstrated that modulated vibrotactile stimuli made the subjects perceive a higher displacement in the middle range of applied forces. This makes us believe that a vibrotactile stimulation on fingertips causes a sensation of elbow joint displacement under finely tuned conditions when the pseudo-haptic effect does not prevail over the haptic illusion effect.

The experiments were performed using a custom made vibrotactile controller incorporating a six-axis force sensor and a voice-coil actuator. As for the future work, we aim in increasing the number of the degrees of freedom. All the experiments conducted in this work considered the perception of elbow displacement on a single axis only. The developed setup incorporates a six-axes force sensor that allows us to detect the lateral and rotational forces.

As an extension and application of this phenomenon, we can vary a softness of the objects sensed in the VE.

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