Validation of a Soft Pneumatic Unit Cell (PUC) in a VR Experience: A Comparison Between Vibrotactile and Soft Pneumatic Haptic Feedback

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***Abstract*—Soft pneumatic displays have shown to provide compelling soft haptic feedback. However, they have rarely been tested in Virtual Reality applications, while we are interested in their potential for haptic feedback in the metaverse. Therefore, we designed a fully soft Pneumatic Unit Cell (PUC) and implemented it in a VR button task, in which users could directly use their hands for interaction. Twelve participants were asked to enter six-digit sequences, while being presented with PUC feedback, vibration feedback (VT), or no haptic feedback. Metrics on task performance, kinematics and cognitive load were collected. The results show that both vibration and PUC feedback resulted in participants pressing through the back of buttons less. The kinematic data showed that participants moved more smoothly during PUC feedback compared to vibration feedback. These effects were also reflected in the questionnaire data: participants felt more successful when using either PUCs or VTs, but they perceived the lowest level of stress when using PUCs. Feedback preference ratings also showed that PUC was the most preferred kind of feedback. Concluding, our array of metrics confirm that PUCs are good alternatives for haptic feedback in VR tasks in which electromechanical vibration motors typically excel: creating virtual button clicks.**

***Index Terms*—Soft robotics, Virtual Reality, virtual buttons, task performance, kinematics, questionnaire, vibration, soft pneumatic actuator.**

I. Introduction

Haptic feedback has long promised to hold the key to creating truly immersive experiences in the metaverse. The north star is a lightweight, low-encumbrance device that can be worn on the hand or finger tips, such as a haptic glove or thimble. In the past decade, many gloves and thimbles have been developed, both in academia (see [1] for a review) and in industry (see [2] for a review). Despite this boom in glove and thimble development, the only type of haptic feedback that is broadly implemented commercially, in for instance phones and game controllers, is vibratlion feedback from electromechanical vibration motors [3]. One of the reasons for the slow adaptation of haptic techniques might be that many of the haptic feedback gloves and thimbles are bulky and uncomfortable for the user [1], [2]. To create wearable solutions which are more comfortable and compatible with the softness of human touch, we explore soft robotic techniques to create haptic feedback displays.

Soft robotics is a relatively new field, which often takes inspiration from nature – like elephant trunks and octopus arms – to create soft structures that can move via for instance air [4]. Many authors have previously investigated pneumatically driven (partially) soft displays for haptic feedback to the human hand. For practical implementations of pneumatic feedback in wearable systems with small form factors and sufficient performance, innovations in pump and valve technology are still needed. In recent years we see many promising developments, such as the fiber pumps by Smith et al. [5]. However, these innovations are outside of the scope of this paper, and we focus on the promise of pneumatic actuators for haptic feedback.

One of the first pneumatic cutaneous feedback displays, created by Amemiya and Tanaka [6], used a rigid backing to which actuation tubes were attached, and a softer top layer which was in contact with the human skin. Since then, many of these types of arrays have been produced, even going up to an array size of 100 pixels [7]. We see desktop versions [8], [9], [10], [11], [12] and wearable displays [6], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29]. Most actuators have a rigid base with a soft top layer, or a rigid outer layer with a softer inside layer, but some actuators are fully soft [17], [23]. Although most displays focus on pressure actuation in the normal direction by indenting the finger with a dome, some displays also add shear [22], vibration [17], [20], [21], or thermal actuation [8], [10]. For many displays, extensive physical characterization of the displays is described, and many studies also include psychophysical testing to establish the ideal pixel size, shape, spacing or intensity (e.g. [6], [14], [15], [24], [26]). Thus, there is a large body of work on the physical performance of soft pneumatic displays and their low-level perceptual experience. However, we focus on the use of these types of displays in applied settings.

Several studies have focused on medical applied settings, by adding pneumatic feedback to, for instance, Da Vinci

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tele-operation systems and laparoscopic tools [11], [12], [16], [24], [27], [28], [29]. Most of these studies report benefits of the presence of feedback in terms of a reduction in grip force and an increase in the correct detection of tumor lumps. For a review of this application domain, see Talhan et al. [30]. To explore the application of soft pneumatic feedback in the metaverse, we are focusing on a Virtual Reality setting. In this domain, fewer studies exist. Some works do describe the implementation of pneumatic devices in virtual environments, such as tissue simulations [14], [16], [17]. However, even though the environments were simulated in these studies, the interactions between the users and the virtual worlds were limited. In Hashem et al. [17], users did not receive visual feedback while interacting with virtual textures. In Kim et al. [14] and Fukuda et al. [16], users did receive visual feedback, but the visual information was shown from a fixed viewpoint via a 2D screen, and the users' hand position was represented with a virtual cursor. For our current work, we focus on the implementation of a soft pneumatic haptic display in an interactive Virtual Reality (VR) environment in which the user can directly use their hands for interacting with the virtual world.

As a fully soft pneumatic actuator, we designed a simple Pneumatic Unit Cell (PUC), which we plan to miniaturize and integrate in a larger array in the future. To compare the performance of our PUC against the state of the art feedback in a VR task, we used feedback from an LRA vibration motor [3], [31]. We chose a simple VR task in which vibration feedback usually excels: a virtual button task. Vibration feedback has shown to be very effective at communicating simple binary signals, such as button clicks [31]. By using clever rendering schemes and thorough categorization of vibratory signals, aspects such as the percept of texture [32] or even affective touch [33] can be elicited using vibratory feedback. Nonetheless, vibration feedback is inherently limited by the nature of the electromechanical vibration motor, as the basic signal is always a vibration [31]. We believe that an analogue pneumatic signal is a more promising choice to elicit a broad range of haptic percepts. Moreover, we believe that a fully soft display can provide interesting subtle cutaneous percepts, which would be difficult to simulate using rigid actuators. To assess the effect of the different types of haptic feedback on the participants' experience in the virtual world, we extracted several task performance and kinematic metrics from the participants' hand tracking data. In addition, we assessed the subjective participants' experience using questionnaires. Together, these metrics allowed us to compare the effects of vibrotactile and soft pneumatic haptic feedback on several levels in an interactive Virtual Reality task.

II. Materials and Methods

A. Participants

Twelve right-handed healthy participants, ten men and two women, aged 26±4 years (mean ± standard deviation), took part in the study. Eight participants had used VR a few times, and four had never experienced VR before. All participants were naive to the purpose of the experiment and participated voluntarily. At the start of their experiment, participants signed an informed consent form and received written instructions about the experimental task. Ethical approval for the experiment was provided by the ERB of Eindhoven University of Technology (#ERB2022ME3).

B. Setup

A virtual environment was created using the Unity game engine (Unity Technologies, USA). This environment consisted of a virtual keypad, as shown in Fig. 1(a). The size of the full panel was 35 × 40 × 2.5 cm (width × height × thickness). The number buttons were 6 cm × 6 cm (width × height), while the green button was 6 × 10 cm. Participants wore a VR headset (HTC, Vive Pro VR, USA), to which a Leap Motion hand tracking unit was attached for tracking the participant's hands (Ultraleap, USA). The standard Ultraleap VR Development mount was used for attachment, and the offset between the mounted camera's origin and the headset's origin was corrected for in Unity software. Throughout the experiment, participants used their right index finger for pressing the buttons. Their hands were displayed using the standard Ultraleap 'stick-figure' skeleton, which is shown in Fig. 1(a) and in the Supplementary movies. The overall hand size was automatically scaled by the Ultraleap software to the hand size of the user. The radius of all the spheres depicting joints was 8 mm, while the radius of the connecting links was 6 mm. Whenever participants were wearing the headset, pink noise was played to mask any audio coming from the haptic feedback. The only mildly audible sound was the exhaust of the pneumatic system, so out of an abundance of caution, the PUCs were also actuated in the conditions in which participants did not wear them for feedback.

For an overview of all the hardware components involved in the experiment, see Fig. 2. For vibrotactile feedback, an LRA vibration motor and driver were used (LRA+driver: DA7280, Sparkfun Electronics, USA. LRA model type G1040003D, Vybronics, China). An LRA motor was selected since it is very common in haptic feedback systems, has a low latency, and operates at a low voltage. The vibration motor was attached to the participant's index finger using a soft silicone finger sleeve (Xutong, China), as shown in Fig. 1(b). Whenever a button was engaged (i.e., compressed to at least 75%), a short vibration signal was played. The 'strong click 60%' signal from the built-in library was used, using the DRV2605 L driver (Texas Instruments, USA). This vibration signal was played once upon button engagement.

For pneumatic feedback, PUCs were created using Dragon-Skin 10 silicone (Smooth-On, USA). An open mould design was used to create a 11 × 7 mm (diameter x height) cylinder in two parts, which were glued together after curing using Sylpoxy adhesive (Smooth-On, USA). A small hole was left open in the bottom of the cylinder, in which a flexible silicone tube was glued for pneumatic actuation. An overview of a PUC with its mould is given in Fig. 3. The PUC was attached to the participant's finger using the same soft silicone finger sleeve as used for the vibration motor, but it was cut in a different configuration to give the thicker PUC more space, as shown in Fig. 1(c). Silicone is transparent to infrared light, so the finger sleeve did not interfere with Leap Motion's infrared-based hand tracking measurements.

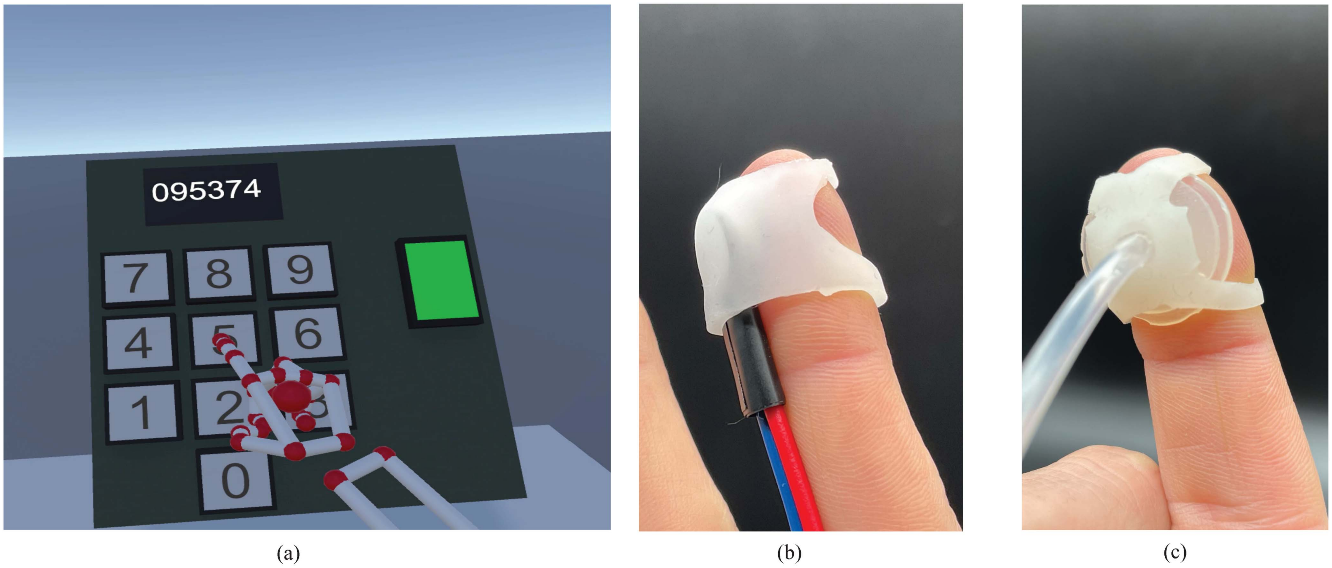

Fig. 1. General overview of the setup. (a) VR scene of a participant mid-trial. Participants were asked to type in the six-digit number shown in the top screen, without receiving visual feedback about the pressed numbers in the top screen. After completing the number, participants pressed the green button to proceed to the next trial. (b) LRA vibration motor used for vibration feedback conditions. The motor was attached with a soft silicone sleeve. (c) Pneumatic Unit Cell (PUC) used for pneumatic feedback conditions. The cylinder was attached using the same soft silicone material as used for attaching the vibration motor.

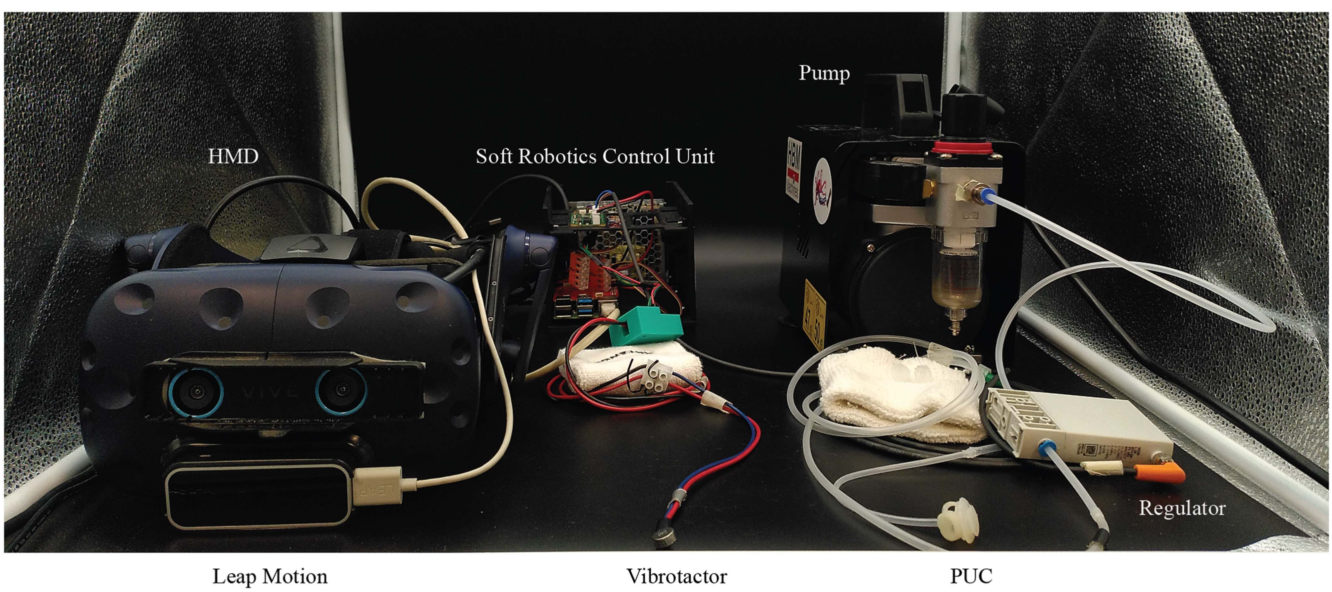

Fig. 2. Overview of all the hardware that was used in the experiment. A Leap Motion controller was attached to the HTV vive headset using a 3D printed mount. We used our Soft Robotics Control Unit (for more details, see [34]) for real-time control of the PUC and VT in response to collision information between the virtual scene and the tracked hands.

For more details on the deformations and frequency response of the PUC, please see [35]. Whenever a button was touched, a virtual spring was simulated between 0% and 75% button compression, by linearly increasing the pneumatic actuation from 0 to 25 kPa. Once the button reached engagement, i.e., when the button was compressed more than 75%, the pressure was kept constant at 25 kPa. For button release feedback, the same virtual spring was used.

Both the vibration motor and the PUC were actuated using our custom Soft Robotic Control Unit (see [34]). This is a Raspberry Pi 4B based control box, which uses TCP/IP communication to communicate with a Matlab-based control system. The Unity environment communicated collision information to Matlab, which in turn commanded the Raspberry Pi to send a control signal to the vibration motor or PUC. The vibration motor was driven using a Sparkfun QWIIC control board (DA7280, Sparkfun Electronics, USA). The PUC was driven using a three-way proportional valve (type VEAB-L-26-D13-Q4-V1-1R1, Festo, the Netherlands) and a compressor (HBM AS 18 A Airbrush compressor, HBM Machines, the Netherlands). For a more

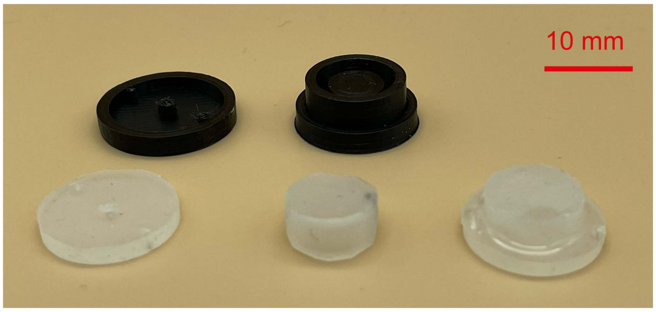

Fig. 3. Details of manufacturing a PUC, with moulds in the back row, and silicone DragonSkin 10 results in the front row. Left) Bottom half with its mould. A tube will be glued into the hole after assembly. Middle) Top half. Right) Complete PUC, after gluing the two cured parts together with Sylpoxy adhesive.

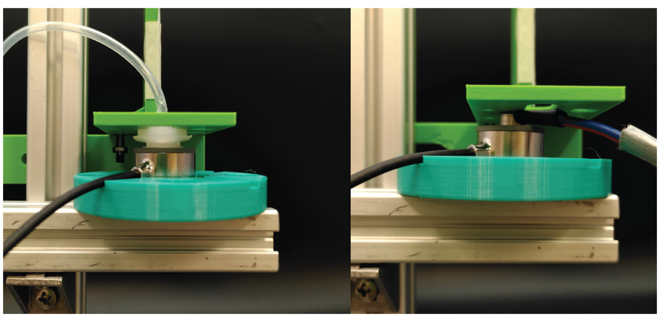

Fig. 4. Setups for characterization of actuators using a 6-axis force sensor. Left: PUC. Right: vibrotactor.

complete description of the architecture of the control box and its performance, please refer to [34].

To characterize the response of each of the actuators, a force sensor (HEX21, 6-axis F/T sensor, Wittenstein, Igersheim, Germany) was placed below the actuator and sandwiched within a rigid frame (see Fig. 4). Force sensor data was collected at 1000 Hz. The same software and hardware configurations as present in the experiment were used to send a characterization signal from Unity through Matlab to the Soft Robotics Control Unit. For the PUC, a 0.5 s step signal was used. For vibrotactile feedback, 1 vibration command of the type ‘strong click 60%’ from the built-in library of the DRV2605 L driver was used. Both the command signal and the force sensor data were stored in Matlab for offline analysis. Both signals were repeated 10 times. The response time was defined as the time between sending the command signal and registering that the force had increased above the baseline signal by 10% of the maximum signal measured on that trial. The baseline was defined as the average of the first 20 force measurements obtained after the command signal was given. The response time of the PUC was 41 ± 14 ms, while the response time of the vibrotactile actuator was 13 ± 3.1 ms. All force traces and response times are shown in Fig. 5).

C. Protocol

At the start of each trial, a six-digit number appeared on the virtual display at the top of the panel, which remained there for the complete trial. Participants were asked to type in the number as quickly and accurately as possible using their right index finger. They did not receive visual feedback in the top display, i.e., the numbers that they typed in were not shown in the top display. Once they felt that they had completed the six-digit sequence, they pressed the green button, and the next number appeared. Corrections were not possible.

Each virtual button consisted of a virtual cube that could move only perpendicularly to the static display between predefined limits when it was touched by a finger. Once the button was fully pressed and thus hit the predefined limit, it remained there even when the participant moved their hand further. The virtual hand did keep following the physical hand. Only one button could be interacted with at a time. A button was registered as engaged when it was pressed to at least 75% of its travel. A button first had to be released completely before it could be registered as engaged again.

Six conditions were tested: three types of Haptic feedback (PUC, VT, and None) and two types of Button travel (Short and Long). The Short buttons had a maximum travel distance of 3 cm perpendicular to the display’s surface, while Long buttons had a maximum travel distance of 6 cm. For both button travel types, the button surface was flush with the panel surface when it was fully compressed. Button travel was introduced as a variable, since we hypothesized that VT feedback might be more useful for buttons with a short travel, which would be closer to keys on a laptop keyboard, while PUC feedback might be more informative for buttons with a longer travel, which would be closer to large spring-loaded buttons. Conditions were presented in blocks, meaning that in each block a single type of feedback and a single type of button travel was presented. Each block consisted of 20 six-digit numbers. A fixed set of 20 six-digit numbers was used for all conditions and participants to make sure that the difficulty was kept constant. These numbers were generated randomly, the only requirement being that each six-digit number consisted on six unique numbers. In each condition the order of this set was randomized. The order of the conditions was pseudo-randomized between participants using a balanced Latin square.

Each participant first received a practice session, in which they typed in five six-digit numbers. They did not receive any haptic feedback during practice. The button travel type matched the type that would be presented in their first experiment condition. Practice session results were not analyzed.

Between blocks, which generally took about five minutes, participants were asked to remove their headset and haptic devices. They filled out the short version of the NASA-TLX questionnaire to assess their cognitive load during the block, using on a 10-point Visual Analog scale with the following six questions [36]:

- How much mental and perceptual activity was required?
- How much physical activity was required?
- How much time pressure did you feel due to the pace at which the tasks or task elements occurred?
- How successful were you in performing the task?
- How hard did you have to work (mentally and physically) to accomplish your level of performance?

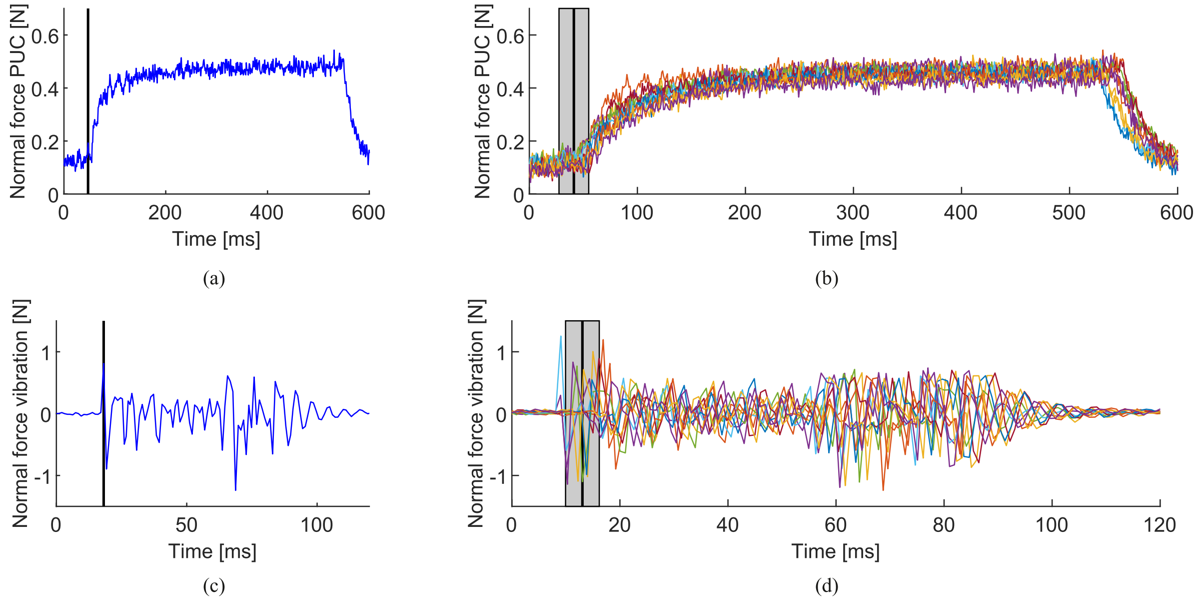

Fig. 5. Characterization results of actuators, with the top row showing PUC data and the bottom row showing vibration data. (a) and (c): Typical examples of a single characterization measurement, with the vertical black line indicating the response time for this measurement. (b) and (d) All 10 characterization measurements overlaid. Each color represents one measurement. The vertical black line indicates the mean response time, and the shaded boxes indicate ±1 standard deviation in response time.

- How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

After completing the questionnaire, participants were encouraged to take a break before proceeding to the next block. After completing the final block and the final NASA TLX questionnaire, participants filled out a general questionnaire to compare the conditions against each other. They were asked to imagine using the haptic feedback on a daily basis in a VR application, and to sort the feedback types according to their preferred type of feedback for this task. At the end, there was a field for free-form responses. The total experiment took about 45 minutes.

D. *Analysis*

Throughout the experiment, the right index finger, palm and wrist, were tracked with a frequency of 60 Hz. Simultaneously, the state of the virtual button objects was tracked, i.e., their collisions with the index finger and their compression depth. Trials in which no buttons were pressed were excluded from further analysis, which was the case for 12 of the 1520 trials. These trials usually represented trials in which participants accidentally pressed the green button twice. For all remaining trials, the movement section and button states between the index finger touching the first number button and the index finger releasing the last number button (excluding the green button) were selected. The button state data for this selected section of the trial were used to abstract the following performance metrics: total completion time, time spent on buttons, percent correct, ratio of trials with double presses, ratio of trials with misses. Total completion time and time spent on buttons were calculated for correct trials only, while for the other metrics, all trials were used. Time spent on buttons was defined as the time that participants spent in contact with the buttons. Missed buttons were defined as buttons that were touched but not engaged (i.e., they were not compressed to 75%). Double presses were defined as buttons that were released before being pressed again. For further analysis, the movement data of the index finger tip was low-pass filtered using a second-order Butterworth filter with a 10 Hz cut-off frequency. From this data, the following movement metrics were calculated: total path length, distance pressed through buttons, mean velocity, and mean acceleration. All these metrics were calculated for correct trials only. For both the performance and the movement metrics, averages across trials per condition and participant were taken for statistical analyses. The NASA-TLX questionnaires lead to six cognitive load metrics. The final questionnaire produced a direct subjective preference metric.

The effect of Haptic feedback type (VT, PUC or No) and Button travel (Short or Long) on all the metrics was investigated using 2-way repeated measures ANOVAs for each metric type. When significant main and/or interaction effects were found, Bonferroni-corrected posthoc test were used for further analysis. To investigate the effect of the order in which conditions were presented (block 1 through 6), a 1-way repeated measures ANOVA for each metric type was performed. For all statistics, Green-House Geisser corrections were applied when sphericity was violated, and an α-criterion of 0.05 was used for significance testing.

III. Results

A. *Performance Metrics*

The performance metrics are shown in Fig. 6. Three of the repeated measures ANOVAs showed significant effects of Button travel on the performance metrics. The 'Total button time' metric was significantly higher for the Long travel buttons ($F_{1,22} = 16$, $p = 0.002$, $\eta_p^2 = 0.59$). It was also significantly affected by

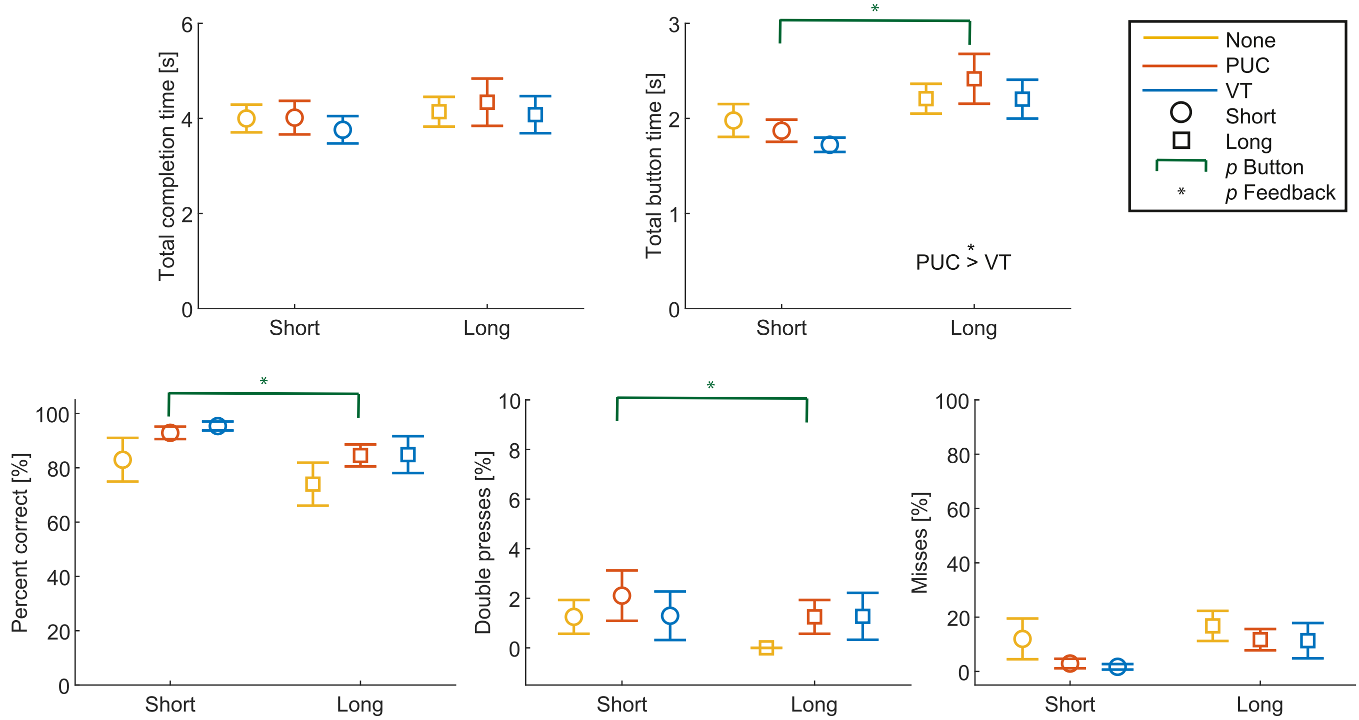

Fig. 6. Results from performance metrics, with colored bars showing the means across participants, and colored error bars indicating ±1 standard error. Colors indicate haptic feedback types, while markers indicate button travel type. Significant main effects of Button travel are indicated with green lines above the graphs. For significant main effects of Haptic feedback, the posthoc testing results are shown in text at the bottom of each graph. Asterisks indicate $p < 0.05$. Note that for three of the five metrics, there was a significant main effect of Button travel. Only for Total button time, PUC feedback led to significantly larger time spent on the buttons than VT feedback did.

haptic feedback type ($F_{1,22} = 4.8$, $p = 0.018$, $\eta_p^2 = 0.31$), with posthoc tests showing that PUCs resulted in significantly longer times spent on buttons than VT feedback did ($t = 3.0$, $p = 0.019$). The 'Percent correct' metric scored significantly higher for the Short buttons ($F_{1,22} = 5.9$, $p = 0.033$, $\eta_p^2 = 0.35$). The 'Double presses' percentage was significantly lower for Long travel buttons ($F_{1,22} = 6.3$, $p = 0.029$, $\eta_p^2 = 0.36$). These effects indicate that Long travel buttons took more time and resulted in more errors. However, for Long travel buttons fewer of these errors were caused by Double presses, compared to Short travel buttons. None of the other main effects or interaction effects reached significance (all $F \leq 2.8$, all $p \geq 0.081$).

B. Kinematic Metrics

The kinematic metrics are shown in Fig. 7. The repeated measures ANOVAs showed several significant main effects. 'Total path length' was significantly higher for Long travel buttons ($F_{1,22} = 9.6, p = 0.010, \eta_p^2 = 0.47$). 'Distance pressed through button' was significantly affected by both Button travel ($F_{1,22} = 17$, $p = 0.002$, $\eta_p^2 = 0.61$) and Haptic feedback ($F_{1,22} = 11$, $p < 0.001$, $\eta_p^2 = 0.50$). Posthoc testing showed that both PUCs and VTs led to significantly smaller distances pressed through buttons than None did ($t = 4.7$, $p < 0.001$ and $t = 2.8$, $p = 0.032$, respectively), while VT and PUC did not differ significantly from each other ($t = 1.9$, $p = 0.22$). 'Acceleration' was significantly affected by Haptic feedback type ($F_{1,22} = 6.4$, $p = 0.006$, $\eta_p^2 = 0.37$). Posthoc testing showed significantly lower Acceleration metrics for PUC compared to VT ($t = 3.4$, $p = 0.007$), and significantly higher Acceleration for VT compared to None ($t = 2.7$, $p = 0.043$). None of the other main effects or interaction effects reached significance (all $F \leq 1.9$, all $p \geq 0.17$).

C. Cognitive Load Metrics

The results from the six cognitive load questions of the shortened NASA-TLX questionnaire are shown in Fig. 8. Repeated measures ANOVAs showed significant effects of conditions on three metrics.

For 'Physical activity', there was a significant effect of Haptic feedback type ($F_{2,22} = 8.8$, $p = 0.002$, $\eta_p^2 = 0.45$). Posthoc testing revealed that conditions with haptic feedback were perceived as significantly less physically demanding than the condition without (None vs VT $t = 3.5, p = 0.006$, None vs PUC $t = 3.8, p = 0.003$), while there was no significant difference between PUC and VT ($t = 0.27, p = 1.0$).

For 'Stress', there was a significant effect of Haptic feedback type ($F_{2,22} = 8.4$, $p = 0.036$, $\eta_p^2 = 0.26$). Posthoc testing revealed that PUC was perceived as less stressful than VT ($t = -2.7 p = 0.044$), while none of the other comparisons reached significance (both $t \leq 2.1$, both $p \geq 0.15$)

For 'Perceived success', both Button travel ($F_{1,22} = 11$, $p = 0.006$, $\eta_p^2 = 0.51$) and Haptic feedback type ($F_{2,22} = 8.1$, $p = 0.002$, $\eta_p^2 = 0.42$) showed significant effects. Their interaction was not significant ($F_{2,22} = 0.68$, $p = 0.52$, $\eta_p^2 = 0.058$).

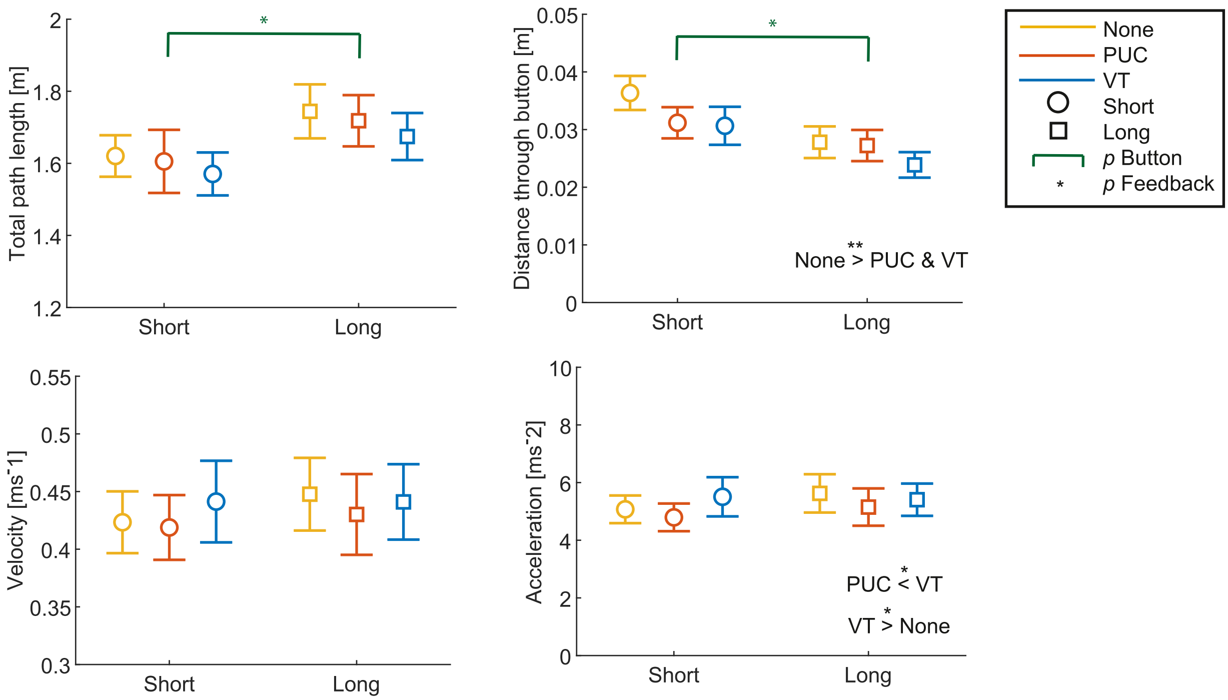

Fig. 7. Results from kinematic analysis of the right finger tip, with colored bars showing the means across participants, and colored error bars indicating ±1 standard error. Colors indicate haptic feedback types, while markers indicate button travel type. Significant main effects of Button travel are indicated with green lines above the graphs. For significant main effects of Haptic feedback, the posthoc testing results are shown in text at the bottom of each graph. Single asterisks indicate $p < 0.05$, double asterisks indicate $p < 0.001$. Posthoc testing showed that PUC and VT feedback both led to smaller distances pressed through buttons, compared to None. Acceleration was significantly lower for PUC compared to VT, indicating that participants moved more smoothly when wearing PUCs.

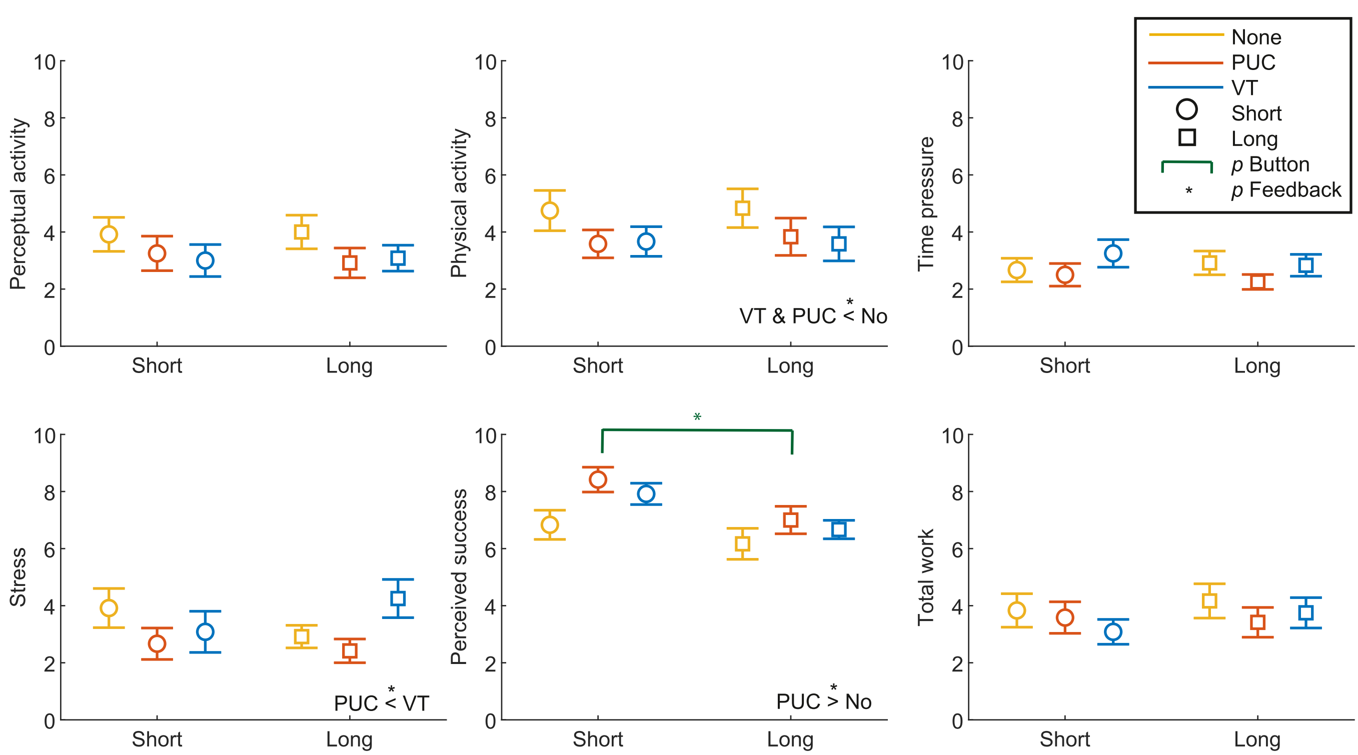

Fig. 8. Results from NASA TLX cognitive load questionnaire, with colored bars showing the means across participants, and colored error bars indicating ±1 standard error. Colors indicate haptic feedback types, while markers indicate button travel type. Significant main effects of Button travel are indicated with green lines above the graphs. For significant main effects of Haptic feedback, the posthoc testing results are shown in text at the bottom of each graph. Asterisks indicate $p < 0.05$. The posthoc tests showed that for Physical activity, both types of haptic feedback resulted in a significant decrease in activity. Participants perceived themselves to be more successful when wearing PUCs compared to None. PUCs were also perceived as being less stressful than VTs.

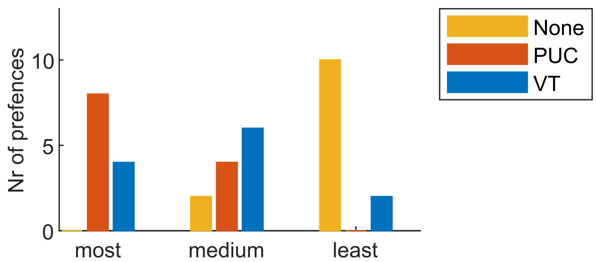

Fig. 9. Haptic feedback preference ratings, which were collected after completion of the experiment. Haptic feedback was preferred over None, with PUC being the most commonly chosen as the favorite feedback type. None of the participants selected PUCs as their least preferred feedback method.

Posthoc testing showed that PUCs were perceived as more successful than None was ($t = -4.0p = 1.0$), while none of the other comparisons reaching significance (both $t \leq 1.37$, both $p \geq 0.05$).

None of the other main effects or interaction effects were significant (all F ≤ 3.68, all $p \geq 0.067$).

The results for the preference rating, which participants performed at the end of the experiment, are shown in Fig. 9. As most participants had not noticed the difference between the button travel conditions, they were only asked to choose their preferred haptic feedback method. These results show that all participants preferred haptic feedback over None. Eight out of the twelve participants chose PUC feedback as their most preferred type of feedback. None of the participants selected PUC feedback as their least preferred type of feedback.

D. Control Analyses

We performed two extra analyses to test for additional effects in our data. In the first analysis, we looked at the effect of the order in which the conditions were presented to the participants. This analysis showed significant order effects for the parameters 'Total completion time' ($F_{5,55} = 7.3$, $p < 0.001$, $\eta_p^2 = 0.40$), 'Velocity' ($F_{5,55} = 8.3$, $p < 0.001$, $\eta_p^2 = 0.43$), and 'Acceleration' ($F_{5,55} = 6.5$, $p < 0.001$, $\eta_p^2 = 0.37$). The parameters with significant order effects are shown in Fig. 10. In the second analysis, we investigated if the actuation of the vibration motor increased the measured velocity or acceleration metrics, when recording the movement of a non-moving finger. Ten sections of 5 seconds of VT actuation were interleaved with ten 5 s sections of no actuation. The results for this analysis are shown in Fig. 11. Two Student's t-test showed that neither the mean velocity data ($t_9 = -1.6$, $p = 0.13$) nor the acceleration data ($t_9 = -1.1$, $p = 0.31$) were significantly different between data sections when the vibration motor was on and when it was off.

IV. Discussion

The goal of our study was to compare the performance of our PUC against vibrotactile feedback in a simple VR task in which vibration feedback usually excels: a virtual button task. Our task was probably relatively easy for participants, given the high percent correct scores overall, and the average cognitive load scores of around 4 on perceptual activity and total work, even for conditions without haptic feedback. This could indicate that the visuals of the virtual hand contacting the buttons and the buttons moving in response provided compelling information. This might also explain why not many of the direct task performance metrics showed significant differences between conditions. Most participants hardly scored double presses or misses. The total completion time for a six-digit number was also low compared to other studies, such as [14] reporting completion times for single buttons presses around two seconds. It is interesting that total completion time did not differ significantly, even though the physical response time of the PUCs was on average 28 ms slower than the VTs were. Most likely, both feedback methods were still sufficiently fast to not limit the participants in their behaviour.

Nonetheless, we do see interesting effects of haptic feedback in the kinematic metrics. The 'Distance pressed through button' metric shows that both PUC and VT feedback caused participants to be more aware of when the buttons have engaged. Moreover, the 'Acceleration' metric shows that participants moved more smoothly when wearing PUCs, compared to VT. The 'Time spent on button' metric shows that participants spent more time on the button with PUC feedback, compared to VT feedback. Interestingly, this effect was not present in the 'Total completion time' metric, so participants must have 'lost' time with VT feedback in between buttons. There might also be a relation between the slower onset of the PUC compared to the VT, the longer time spent on buttons, and the smoother movements for PUC feedback, but further experiments would be needed to confirm this hypothesis.

The questionnaire data show that participants perceived the physical task demand to be lower with haptic feedback compared to None. Additionally, PUCs had the benefit of a larger perception of success compared to None, and PUCs caused a lower perception of stress compared to VTs. The final preference rating also clearly shows that most participants selected PUCs as the most preferred feedback type, and no participants selected PUCs as the least preferred feedback type. Taken together, our array of metrics has confirmed that PUCs are good alternatives for haptic feedback in Virtual Reality tasks in which electromechanical vibration motors have been shown to excel: creating virtual button clicks.

We manipulated the Button travel parameter, because we hypothesized that VT feedback might be most useful for laptop-like buttons with a Short travel, while PUC feedback might be most useful for large spring-loaded-like buttons with a Long travel. For Long travel buttons, the simulation of the virtual spring using the PUC feedback could have been more compelling. We did find significant effects of Button travel on many of the metrics, but none of the interactions between Button travel and Haptic feedback type were significant. Thus, our hypothesis about VT feedback being most useful for Short buttons, and PUC feedback being more useful for Long buttons was falsified. It is worth noting that, although our button travel types were inspired by real counterparts, the scale of our buttons is larger than that

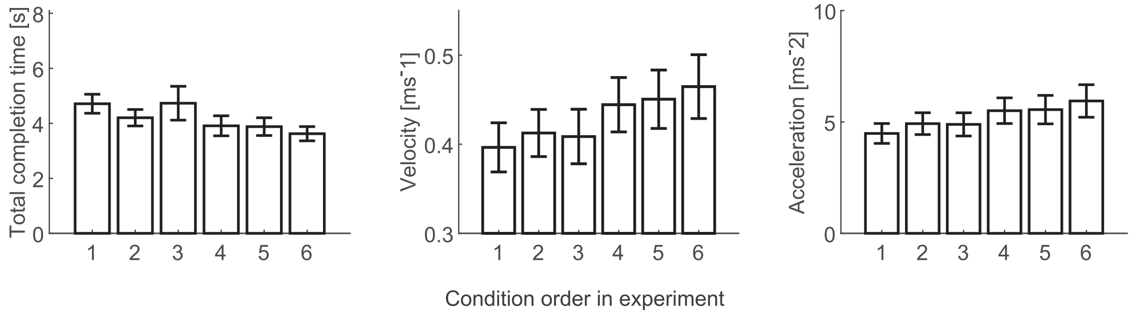

Fig. 10. Results from the effect of the order in which the conditions were presented on the measured performance and kinematic metrics. Order number 1 means that this is the first condition that the participant performed, irrespective of haptic feedback type or button travel type. Only the metrics for which a significant order effect were found are shown, which are from left to right: Total completion time, Velocity, and Acceleration. All these metrics are related to the speed with which participants were moving, which systematically increased across conditions. Do note that the order of the conditions was counterbalanced across participants, so these order effects are balanced out in the main results.

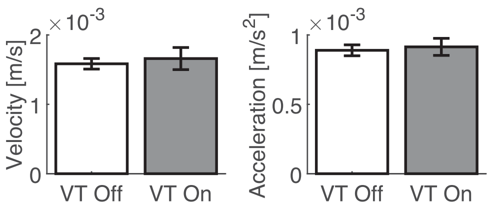

Fig. 11. Results from the control experiment to test the effect of actuating the vibration motor on the average velocity and acceleration recordings for a non-moving finger. Bars indicate the mean across the 10 repetitions, while the error bars indicate ± 1 standard deviation. There is no statistical difference between the vibration motor being on or off in either of these data sets.

of regular buttons on a physical keyboard. We chose this scale because during in-air typing, precise control of finger position is much more difficult than during surface-based interactions. We were also not attempting to create the most realistic scenario, but we aimed to choose a commonly used VR interaction paradigm, and test the effect of adding the two types of haptic feedback to this scenario.

Interestingly, almost all participants indicated during the final direct feedback comparison that they had not noticed the difference between Long and Short button travel, since they only were told about the manipulation after completing the experiment. Nonetheless, all the different types of metrics show a significant effect of Button travel on at least one metric. This is most prominent in task performance metrics, with participants moving faster and pressing buttons more successfully for short buttons. The kinematic data also show significant effects of Button travel. The larger distances pressed through buttons for shorter travels could indicate that participants actually did not change their movements patterns, and thus pressed through shorter buttons further. However, the total path length metric does reveal that path length was shorter for shorter buttons, indicating that participants did change their movements in response to Button travel. Even the questionnaire metrics show that participants perceived themselves as being more successful with shorter buttons. Thus, the virtual experience was intuitive enough that participants changed their behavior unconsciously.

Given the positive results in the current study, we plan to extend our work on PUCs. For achieving broad adaptation of pneumatic solutions for wearable VR feedback applications, issues like the size of the pump and the valves and the durability of the material would still need to be improved. However, we focus on the interaction between human and actuator, and plan to use existing control solutions to investigate the use of PUCs for various types of feedback. For single units, we plan to explore other types of dynamic signals. We also are interested in exploring feedback directions other than normal to the finger, to create for instance slip or tactile softness feedback. When integrating multiple PUCs in an array, we would like to explore the utility of spatial and temporal patterns. Moreover, we would like to test the experience of PUCs in richer multi-modal experiences, which could for instance include audio or temperature cues. For all these avenues of exploration, we plan to focus on assessing the usefulness of PUC feedback for creating tangible virtual objects in Virtual Reality and tele-operation settings.

V. Conclusion

We compared the performance of our soft Pneumatic Unit Cells (PUCs) to that of Vibrotactile haptic feedback in a VR button task. Both VT and PUC feedback resulted in participants being more aware of when they had reached the end of the button. While there were no significant differences in total completion time between the two types of haptic feedback, the acceleration data does suggest that participants moved more smoothly when wearing PUCs, compared to wearing VTs. The questionnaire data align with these observations: participants felt more successful when using either PUCs or VTs, but they perceived the lowest level of stress when using PUCs. The direct preference rating also gave a strong indication that PUC was the most favorite kind of feedback. Taken together, our array of metrics has confirmed that PUCs are good alternatives for haptic feedback in Virtual Reality tasks in which electromechanical vibration motors have been shown to excel: creating virtual button clicks. These results give us confidence that continued PUC miniaturization and integration of PUCs in arrays is worthwhile for exploring its use for creating other types of haptic sensations, such as slip or softness, in Virtual Reality applications.

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