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Touching Virtual Shapes: Combining Kinesthetic and Tactile Feedback in a Single Haptic Device

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***Abstract*—Virtual training environments are powerful tools for various applications. To increase the immersion and realism of these environments, several devices have been developed capable of rendering a wide range of haptic sensations. As humans mainly interact with objects using their hands, the main focus of research has been on developing devices capable of providing feedback to the hand and fingers. Currently, most of these devices only provide one form of feedback, either kinesthetic feedback to finger posture or tactile sensations in the form of pressing or skin stretching. These devices seldom provide more than one kind of feedback while remaining compact enough to be wearable with a natural range of motion of the hand.**

In this work, we present a device that combines an existing kinesthetic feedback glove with a novel tactile fingertip display. The haptic display consists of a cable-driven platform, powered by a stand-alone actuation module. It has been designed to be compact enough for a near-natural range of motion, with the possibility of multi-finger applications in mind. To validate the design, we conducted an experiment with 16 healthy young participants who were asked to reproduce virtual shapes with their index fingers after exploring those shapes under two different conditions: 1) with purely kinesthetic feedback, and 2) with kinesthetic feedback and tactile feedback. The outcome metrics were the exploration time, reproduction time, and reproduction error. For each testing condition, the workload and motivation of the participants were also evaluated.

We found that participants had a lower reproduction error and used more time to reproduce the shapes with the novel haptic display enabled compared to purely kinesthetic feedback. We did not find significant differences in exploration time, workload, or motivation between testing conditions.

Thus, the combined feedback provided by our novel device leads to better performance in shape reproduction compared to only kinesthetic feedback. Further, our device is lightweight and compact, potentially enabling multi-finger use which may lead to even greater performance and immersion in virtual object manipulation tasks.

I. Introduction

Wearable haptic displays are used in a wide range of applications to allow interaction with virtual objects. They aim at providing physical stimulus to its user in addition to purely visual feedback. Examples of applications include Virtual Reality (VR) training of otherwise expensive and inaccessible tasks [1], teleoperation [2], immersive VR experiences [3] and rehabilitation [4]. By creating devices that allow physical interaction with virtual scenarios, a higher level of immersion can be achieved [5]. This increased immersion leads to subjects being more engaged with the task at hand, resulting in better rehabilitation of neurological injury and more efficient learning [6] [7] [8].

Within the several developed haptic displays, there are two distinct forms of feedback that are being provided. The first form of feedback is kinesthetic feedback to the fingers. This allows a device to control the range of motion of a finger by blocking its movement, for example when in contact with a virtual object. These devices provide the user with information about the dimensions of virtual objects, as the device controls the amount the user can close their hand around a virtual object. The most common way this is achieved is by having electromagnetic brakes, servo-motors or DC-motors apply force to the finger via either rigid bodies [9] or flexible tendons [10].

The second category of devices provides tactile feedback. These devices provide information about textures, normal and tangential forces, or local surface orientation of virtual objects to the user. A common design that can be found are systems that incorporate a band driven by two electric motors [11] [12]. The band provides a shear sensation to the fingertip by engaging both motors in the same direction. Alternatively, by engaging the motors in opposite directions a normal force can be applied. Due to their design and the required tension on the band, contact with the fingertip is never broken. This can be detrimental to immersion when no virtual object is touched, as feedback is provided when none is required. A system with the same two degrees-of-freedom sensation that is capable of removing contact was designed by Tsetserukou et al. and uses rods instead of a band [13]. Besides band-driven devices, there are also platform-based solutions driven by servo motors. These designs commonly use two or more servos on the back of the distal digit of the finger to drive a platform on the fingertip using strings [14], rods [15], or gears [16]. These systems are capable of presenting sensations at multiple locations on the fingertip and are able to completely remove contact as well. However, current tactile feedback devices are large in size. Most devices have both the haptic interface itself and the motors or servos powering them mounted on the finger itself. Using multiple haptic interfaces on different fingers at the same time on a single hand can result in them obstructing the natural range of motion of the fingers. This results in multiple-finger stimulation not being possible.

While studies have shown how useful both kinesthetic and tactile feedback devices are when interacting with virtual objects, relatively few studies have combined these two modes of feedback into a single device. Baik et al. [10] combined kinesthetic and tactile feedback in a device that provides kinesthetic feedback to finger posture via tendons and presents a tactile sensation at the fingertip with tubes. The tactile feedback is an applied force in a singular location at the fingertip. Despite the relative simplicity of this feedback, experiments with this system already provide significant improvements to the perceived realism and acuity of contact forces. However, a tactile sensation at a singular location on the fingertip is still not representative of how humans normally sense objects with their hands. When interacting with objects, our fingers rarely make contact with objects with a uniform, singular area on the fingertip. Instead, the contact area varies depending on the object's shape, the angle at which we are touching the object, and the amount of force we exert onto the object.

In this work, a novel haptic device is presented that can be integrated with an existing kinesthetic feedback device. The novel interface consists of a remotely actuated tilting platform driven by cables. It was designed to be compact while still providing tactile feedback in more than one location on the fingertip, and hampering the natural range of motion of the finger as little as possible. In addition, it can completely break contact with the interface when no tactile feedback is required. The kinesthetic feedback device is provided with a simplified version of the Senseglove Nova. The Senseglove Nova is a softglove hand exoskeleton used for VR training able to provide kinesthetic feedback on finger posture for up to three fingers and the thumb using electromagnetic brakes and a series of cables guided along the finger.

To verify the design, a within-subject experiment on exploring the shapes of virtual objects was performed. There were two test conditions. The first test condition was purely feedback from a kinesthetic feedback glove. The second test condition included tactile feedback from the novel haptic display. The experiment was performed with only the index finger and constrained hand movement, to study the effects of the design in a more isolated setting. The outcome metrics consisted of reproduction error, exploration time, and reproduction time. Additionally, two standardized questionnaires were used to assess the participant's user experience. The Intrinsic Motivation Inventory (IMI) inquiry was taken for the categories perceived competence, effort/importance, and interest/enjoyment [17]. The raw NASA TLX (RTLX) [18] was employed to measure the participants' subjective mental workload.

We expected that the addition of the novel haptic display would enhance the reproduction of the virtual shapes explored. We hypothesized that this would be reflected in lower errors when reproducing the explored shapes, with shorter exploration time required for each shape. Finally, we hypothesized that the required effort and experienced workload would be lower for the condition that includes the novel haptic display, due to more information about the object being available to the participant.

II. Methods

Fingertip Haptic Device

A. Design requirements

This research was performed in cooperation with Senseglove, with the ultimate goal being to explore the possibility of integrating a novel tactile haptic interface with their existing product, the Senseglove Nova. The Senseglove Nova is a compact device that allows for a near-natural range of motion of the fingers. For the index finger, a natural range of motion means 90° of flexion at the Metacarpophalangeal (MCP), 100° of flexion at the Proximal Interphalangeal (PIP), and 8° of flexion at the Distal Interphalangeal (DIP) [19]. The Nova reduces flexion at the PIP and DIP by approximately 2°. The novel haptic display should reduce this range of motion as little as possible.

Once a collision with a virtual object while wearing the Nova is detected on one or all of the fingers, the electromagnetic brake for the respective finger engages resulting in the respective cable running along the finger being stopped in its track. This in turn results in the finger being held back by the glove, which provides the sensation of actually interacting with the virtual object. Besides this kinesthetic feedback, the Nova is also capable of providing vibrotactile feedback to further increase immersion in certain VR scenarios, for example during virtual vehicle assembly training with a hand drill. This vibrotactile feedback was not included in the prototype developed for this research, to prevent it from distracting participants from the feedback of the novel display that we were evaluating.

The most commonly used techniques to provide tactile feedback considered from literature were devices that deliver their feedback via either bands or platforms. While the band-driven devices have relatively small interfaces with the fingertip itself (the size of the selected band), driving them remotely would impose new problems. To translate the rotation of the motor to a rotation of a band at the fingertip either a rigid transmission or flexible axle would be required. Mechanical transmissions would quickly increase the size of the system, whereas flexible axles introduce a mechanical delay between the motors engaging and the band at the fingertip moving. Additionally, adding new degrees of freedom would require complex mechanisms to change the position or angle of the band on the fingertip. The motor-driven platforms found in literature are generally powered by at least one DC- or servo-motor, which applies force to the moving platform with either strings, rods, or gears. These devices generally provide feedback in more directions than their band-driven counterparts, potentially leading to more immersive virtual object interactions. However, due to their mechanical transmissions and generally larger actuator size, these devices tend to take up more space around the finger. This in turn leads to these devices obstructing a natural range of motion and being harder to use on more than one finger at a time.

Preliminary research resulted in three main design requirements. First, the device needed to be able to provide both kinesthetic feedback to finger posture and tactile feedback to the fingertip. This tactile feedback had to present the local surface orientation of a virtual object. Second, the device needs to allow the complete removal of contact with the fingertip while no virtual object is present. Finally, the interface should be designed with the natural range of motion of the fingers in mind, to not hamper natural finger movement.

B. Hardware design

With a cable-driven system already being in place in the Senseglove Nova and with the integration in mind, the final decision ended up being a platform that is moved against the fingertip using cables. By rotating the platform with two cables it is possible to provide sensations to the fingertip at several locations and it requires little additional space around the finger.

The haptic display provides its tactile feedback via a 3D-printed PLA platform, which is held at a fixed distance from the fingertip by two compression springs (5.7mm when not compressed, spring constant of k approximately 400Nm^{-1}). The platform is kept in the center of the fingertip by two guiding rails, in the same body that houses the springs (component 5 in figure 1). The platform can rotate around its axis in the longitudinal direction of the fingertip with a range of approximately 30° to each side. The body holding this spring and platform is slid into a mount which is permanently attached to the glove.

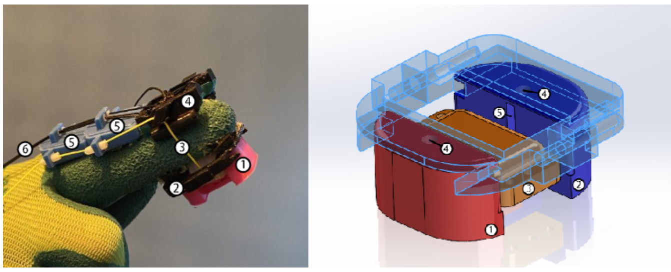

Fig. 1. Overview of the fingertip device (left): (1) Feedback module, (2) mounting module for feedback module, (3) wire connecting the platform to the actuator, (4) mounting module with an attachment point for the wires from the altered SenseGlove Nova, (5) cable guides on the intermediate and proximal phalanges leading the wires toward the actuation module and (6) Senseglove cables for brake and potentiometer. Close-up CAD rendering of the feedback module (right): (1) distal half interface housing, (2) proximal interface housing, (3) platform that interacts with fingertip, (4) holes that house the springs to maintain distance between participant and platform when motors not active, (5) guide for platform axis.

The platform for tactile feedback is actuated remotely by two DC motors (Faulhaber 2342S048C-R 3315 with IE3-32 encoders), while the force feedback to finger posture is provided by an electromagnetic brake (custom order, max. 5N brake force, SG Transmission). The motors transmit their movement to the cable via a form-fitted pulley that is attached to the motor axle. This pulley is attached to the same housing on which the motor is fitted via a wound-up leaf spring, which keeps tension on the pulley and therefore the cable. This spring system is a scaled version of the system that is used in the brake housing and potentiometer housing employed in the Senseglove Nova. The tension was lowered to prevent the leaf spring from bringing the platform in contact with the fingertip when the motors were shut down.

The same cable guiding system along the index finger as the Senseglove Nova is used, with two additional nylon tubed cable guides for the two cables that control the orientation of the platform that provides tactile feedback to the participant's fingertip. Each phalange on the index finger houses one of these cable guides. Cable guides are easily replaced between gloves, as only the mount is permanently attached to the glove, just like with the haptic display itself.

In order to run the experiments, an experimental setup was designed. The experimental setup presents a constrained two-dimensional area of 13.5 by 8 cm within which participants performed the experiment. This frame can be seen in figure 2 as component 7. To track the fingertip position of the participant within this frame two string potentiometers with AS5600 Hall effect sensors are used. These can be seen as the blue bodies on components 3 and 8 in figure 2. One is tracking the location of the finger in the Y-direction of the frame. This sensor detects flexion and extension of the finger as it does in the Senseglove Nova. A second sensor is attached to the cable-guide body on the dorsal side index finger to track movement in the X-direction within the frame.

The cable guides and novel interface are designed to be modular, allowing the glove to be interchangeable for different hand sizes. If a participant is not comfortable with the provided softglove, it can be exchanged for a different size.

The novel haptic interface has not been completely integrated with the Senseglove Nova yet. Instead of mounting the electric components on the dorsal side of the palm, the components are placed on a separate platform (component 1 in figure 2). This allowed for greater access to each individual component for easier replacement and maintenance during development.

C. *Software design*

The control of the device is performed between two Teensy system boards. The main software controlling the angle of the tactile display platform runs on a Teensy 4.1 board. The angle of the platform in the tactile display is controlled by a proportional feed-forward controller. The tracking of the finger position is done by a secondary Teensy 4.0 board to which the potentiometers are connected. Both USB microcontrollers communicate via serial communication with Processing 4.0 running on a laptop.

This laptop also incorporates a visual interface, on which the fingertip position could be shown together with a virtual shape. At the beginning of each experiment, the participant is asked to assume the starting position in the top-left corner of the frame of the experimental setup. That location is then calibrated as the origin of the virtual space. If required, the participant's position within the virtual space can be re-calibrated again mid-experiment by the examiner.

The fingertip's raw position data is collected in Processing 4.0 and is saved at a rate of 59Hz. The Teensy microcontroller control loop runs at a frequency of 59kHz. Processing provides the Teensy microcontroller with new information about the required platform orientation at a rate of 12Hz. This rate was reduced empirically to prevent serial overload.

VALIDATION EXPERIMENT

D. *Participants*

A total of sixteen healthy participants took part in this experiment. Half of them were male while the other half were female. All participants were in an age range from 21 to 35 years, with a mean age of 26.3. All participants were right-handed. The research experiment was approved by the Human Research Ethics Committee of the Delft University of Technology. Informed consent was obtained from all participants prior to the experiment. Participants were not compensated for their participation.

E. *Experimental protocol*

The experiment consisted of a shape-exploration task of virtual objects, where visual feedback was not available. Participants were presented with a series of virtual shapes, seen in 3, and were asked to explore and reproduce each one of them after exploring them using the device on their index finger. Two experimental conditions were tested. One of the experimental conditions consisted in exploring the virtual shapes receiving only kinesthetic feedback to the index finger (condition K). The other condition consisted in exploring the virtual shapes while receiving both, kinesthetic and tactile feedback with our new device (KT). A within-subject study was performed and the order of the two experimental conditions was randomized, with half of the participants starting with the K condition and the other half with KT.

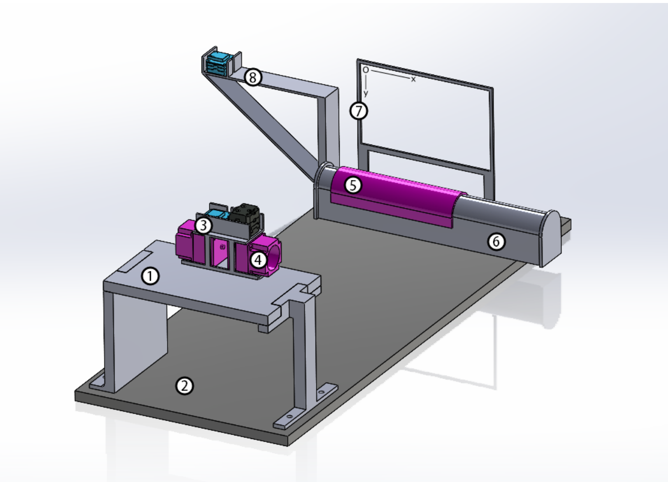

Fig. 2. Render of the novel haptic interface. (1) Platform under which participants are instructed to place their arm. (2) The board on which the whole setup is mounted. (3) The bracket containing the motor mounts. On top of this bracket the original Senseglove brake (right) and potentiometer (left) are placed. (4) Motor mount. (5) A slider on which participants are instructed to place their hand. (6) A rail for the slider to move across is used to constrain movement in the X-direction. (7) The frame that represents the border of the virtual space. (8) Arm housing the second potentiometer.

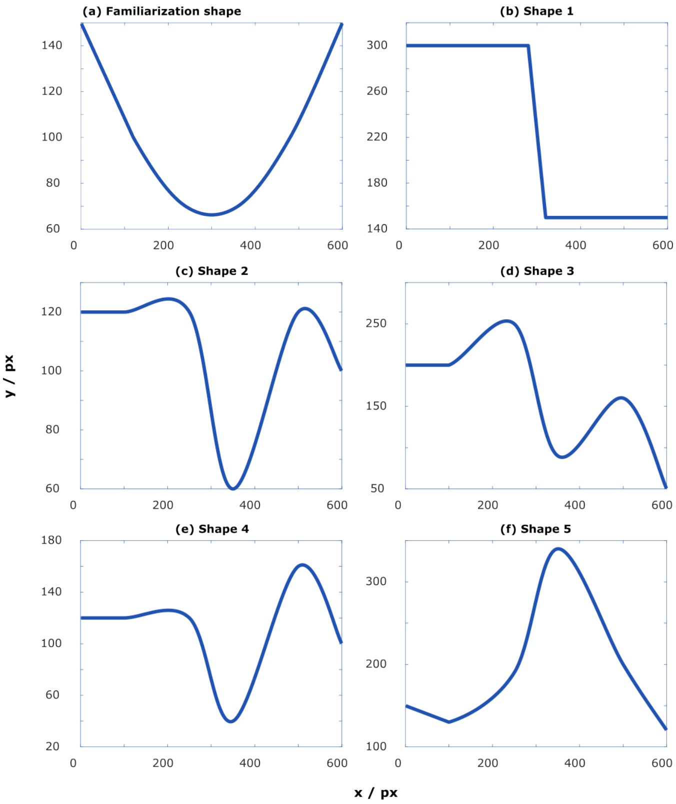

Fig. 3. (a) The shape used during the familiarization phase and (b-f) the shapes 1-5 used during the exploration trials. Shape 1 was always the first one to be performed, and thus was excluded from the analysis to account for familiarization effects. The x and y axes correspond to the rectangular area of the experimental setup (component 7 in figure 2, which is divided into pixels (px) corresponding to the shape representation on the screen (only shown during the familiarization phase).

After receiving the experiment instructions and providing written consent, the participant was instructed to sit behind a desk and disinfect her/his hands. Once ready, the softglove was donned on the right hand. The participant was then asked to rest her/his hand on the slider (component 5 in figure 2) in its starting position all the way to the left. The examiner once again explained the experiment procedure and provided the option to ask any questions before the experiment started. When the participant was ready, the experiment began.

Each participant performed with both experimental conditions and was allowed up to two minutes of familiarization at the beginning of each testing condition. During this time, the virtual shape was visible on a monitor, and the participant could explore it with the respective feedback mode of her/his experimental condition. After this familiarization period, the monitor was shut down and the participants were presented with five virtual surfaces in consecutive order. They were asked to explore each virtual curve using the feedback available provided by the device. Once a participant had an idea of where the boundary of this curve was, the participant could signal the examiner to start a reproduction recording. During the reproduction phase, they were asked to trace the shape with their finger in a smooth continuous motion from left to right while the feedback was turned off. There were no speed requirements for this movement. Each participant received three attempts per shape, resulting in a total of 15 recordings per condition per participant. The curves were always presented in the same order. Between each reproduction, the device switched back into its exploration mode and participants were allowed to use this mode if desired.

The first shape was also considered as familiarization, as it was the first scenario in which participants were asked to reproduce the shapes with the feedback disabled.

After performing all recordings for a single condition, an RTLX and IMI questionnaire were taken. After these questionnaires, the second experimental condition was performed. This second condition is followed by another RTLX, IMI, and a few closing questions.

F. *Outcome Metrics*

To evaluate the effects of the novel haptic interface during the exploration and reproduction of the virtual shapes, three outcome metrics were defined. These metrics are the exploration time, reproduction time, and reproduction error between the explored and replicated shapes.

The exploration time is the amount of time each participant took to explore a shape. The replication time is the amount of time each participant took to replicate a virtual shape. The reproduction error is the Euclidean distance between the reproduced and explored shapes. To account for offsets, both the target shape and position data of the fingertip were averaged around zero in the Y-direction. To account for different movement speeds, the recorded position data were dynamically time-warped in MATLAB (MATLAB R2019b) before calculating the Euclidean distance. The scores from the RTLX and IMI questionnaires were also evaluated with their respective scoring sheets. The outcome values were scaled to 0-100 for increased readability.

G. Statistical analysis

The averaged and time-warped data was analyzed using a Linear Mixed Effects (LME) model to evaluate the effects of adding the novel hardware to the system in *R* (R Studio, version 2022.07.1).

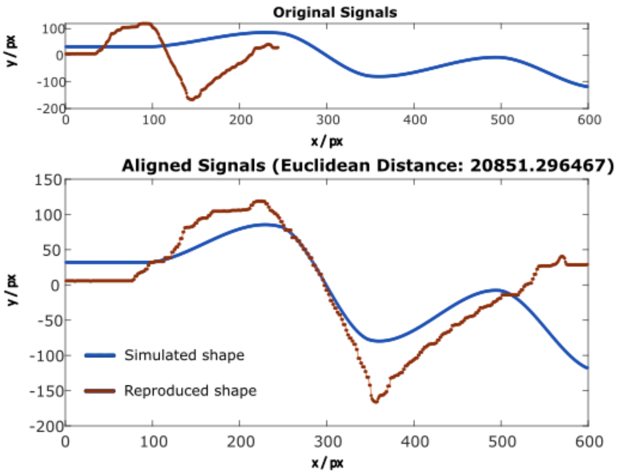

Fig. 4. Example of dynamic time warping of the recorded fingertip position. Both the reproduced (in red) and explored (in blue) shapes were averaged to 0 around the y-axis. The performed movement of the participant is shown in red, the explored shape is shown in blue. The top figure shows the raw position data of the finger, the bottom figure shows the time-warped position data.

The model was applied for the three aforementioned metrics: reproduction error, exploration time, and replication time. The exploration condition (with and without tactile feedback) and shape number were introduced as fixed effects, whereas the individual participants were introduced as a random effect.

For each of the metrics, the outliers were removed. These outliers were defined as values under $Q1 - 1.5IQR$ and values over $Q3+1.5IQR$, with Q1 being the first quartile, Q3 being the third quartile and the IQR being the Inter Quartile Range. This resulted in 20 outliers being removed from the reproduction error, 33 from the reproduction time, and 37 from the exploration time. To confirm assumptions about normality and variance, the QQ plots were visually inspected.

In case of significant effects, a posthoc test was performed using the *emmeans* package [20]. The scores from the raw NASA TLX and IMI questionnaires were evaluated using a one-sided Wilcoxon signed-rank test. All significance was tested with a significance level of $\alpha = 0.05$.

III. Results

A. Reproduction Error

The main effect of the feedback condition (KT or K) was significant for the reproduction error ($p = 0.043$). The different shapes themselves also showed significantly different performances ($p < .0001$). The interaction effect between the type of feedback and the shape number was not significant.

B. Reproduction Time

A significant main effect of the feedback condition on the reproduction time was found ($p = 0.002$). Significantly more time was spent on reproducing the shapes with the novel haptic display enabled when compared to just kinesthetic feedback. No significant effects were found with respect to the different shapes. A significant interaction effect between the different shapes and feedback conditions was found ($p = 0.023$). In particular, shapes 2 and 5 showed longer reproduction times with the novel display enabled than with just kinesthetic feedback ($p = 0.002$ and $p = 0.003$, for scenarios 2 and 5 respectively).

C. Exploration Time

A significant difference in performance was found between the shapes ($p = 0.028$) but no significant effect of the feedback condition was found.

D. Questionnaires

No significant differences were found when studying the results of both the IMI and RTLX. Not only the final scores for each questionnaire were evaluated, but also the separate subcategories of the IMI and the individual RTLX questions were evaluated. The medians, first and third quartiles of both questionnaires can be seen per feedback condition in Table I.

TABLE I
Descriptive statistics for the RTLX and IMI questionnaires

	Kinesthetic median (Q1–Q3)	Kinesthetic and Tactile median (Q1–Q3)
RTLX Total	**41.67 (34.72–47.22)**	**41.27 (37.3–46.43)**
Mental Demand	45.24 (32.14–63.1)	42.68 (32.14–58.33)
Physical Demand	47.62 (27.38–57.14)	52.38 (38.1–58.33)
Temporal Demand	19.05 (4.76–40.48)	16.67 (4.76–29.76)
Performance	50.0 (36.9–64.29)	54.76 (41.67–58.33)
Effort	64.29 (52.38–72.62)	61.9 (51.19–72.62)
Frustration	23.81 (14.28–39.29)	28.57 (11.91–47.62)
IMI Total	**72.22 (57.74–75.99)**	**73.41 (61.9–80.16)**
Interest and Enjoyment	75.0 (55.36–85.71)	75.0 (55.36–85.71)
Perceived Competence	54.76 (47.62–67.86)	64.29 (41.67–67.86)
Effort and Importance	76.19 (57.14–95.24)	78.57 (70.24–91.67)

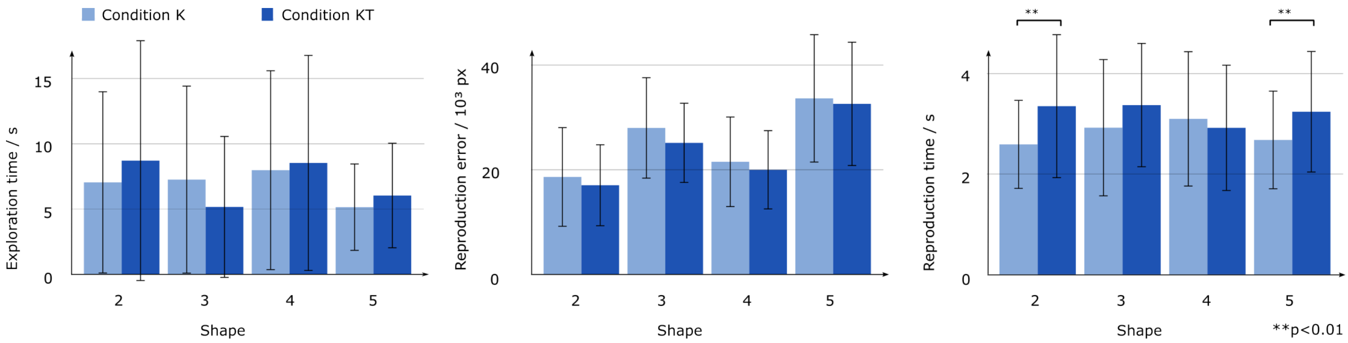

Fig. 5. Experiment results displaying the mean and standard deviation of the exploration time, reproduction error, and reproduction time for each shape and test condition.

IV. Discussion

A. Designing a novel compact haptic display capable of providing tactile feedback while still allowing contact with the fingertip to be broken

While designing the novel interface, several potential improvements were noticed compared to the literature. Prior devices were either too cumbersome, did not provide the required combination of kinesthetic and tactile feedback, or only provided limited tactile sensations. The goal was to develop a novel device that filled these gaps, resulting in a compact device capable of providing tactile and haptic feedback simultaneously, with the ability to fully remove contact with the fingertip.

The novel interface has a weight of only 7 g with dimensions distributed around the fingertip of 30 x 27 x 16 mm (width x length x height) excluding the actuation module. The actuation module is capable of being mounted remotely to remove load from the finger. The novel interface is not in contact with the fingertip when no virtual objects were present. By combining the novel haptic display with the existing Nova hardware both kinesthetic feedback and tactile feedback at a range of points along the fingertip are possible, potentially allowing immersive exploration of virtual surfaces.

The natural range of motion is reduced while wearing the device. The maximum flexion ended up being 70° at the MCP, 92° at the PIP and 65° at the DIP. Finger extension is not hampered while wearing the device. While this reduced flexion is only noticeable when attempting to fully close the fist, which was not required for this experiment, it is something that could be improved before integrating the device with the Nova. A first step to further optimizing the interface would be reducing the size of the mount attached to the glove and the bodies housing the springs. The spring bodies impose a slight reduction in flexion of the finger and the mounts could potentially still make contact with mounts on other fingers in their current state. By further optimizing the hardware and reducing it's size this range of motion could be less restricted, to potentially allow multi-finger use.

B. The combination of tactile and kinesthetic feedback resulted in a better reproduction of virtual shapes

As hypothesized, we found an improvement in the reproduction of virtual shapes after exploring those with both, kinesthetic and tactile feedback, as the reproduction errors became significantly lower with the addition of tactile feedback.

The availability of the feedback could have resulted in the recruitment of additional mechanoreceptors, providing a more salient image of the virtual shape as not only its vertical position but also its local angle was available to the participant during exploration. Additionally, the fingertip tactile feedback could also have allowed users to stay on the shape easier during exploration. The nature of the original kinesthetic feedback demands a sort of tap-and-release means of exploring the shape, as it was not capable of providing tangential forces to the fingertip. The novel interface presents the local angle of the surface, which gives the participant a sense of the direction the shape is going, potentially making it easier to actually track the shape during exploration. Finally, the shifting of the feedback from the left to the right side of the fingertip provides a clearer sense of peaks and valleys, points that are key to knowing the overall shape of a curve.

However, contrary to our hypothesis, the exploration time was not significantly lower with the addition of the novel interface. The reproduction time, however, was significantly longer with tactile feedback enabled. This has led us to believe that because they were receiving more information during exploration, it could have resulted in the participants being more careful in replicating the shape. The same could be said for the lack of information available during the feedback condition with only kinesthetic feedback. With relatively little information being available during exploration, the participants were perhaps less confident in their guesses, resulting in a more careless replication. While the recorded perceived confidence was higher on average for the condition with both kinesthetic and tactile feedback, no significant effect of device state was detected to confirm this.

In summary, the inclusion of tactile feedback by the novel haptic display resulted in a reduction of error in reproducing virtual shapes and could lead to a better overall experience during future virtual reality applications.

C. The additional feedback did not significantly change motivation or perceived workload.

The required effort and experienced workload were hypothesized to be lower for the condition that includes the novel haptic display. However, no significant differences were found in the results from the RTLX and IMI inquiries. The observed results of both questionnaires for both feedback conditions are all in the minimal to intermediate workload range [21]. This could be the reason why participants were not experiencing a significant difference in workload, as the initially perceived workload was already considered as not demanding. The beneficial effects of the novel haptic display on workload may become more discernible in more demanding tasks.

D. Future work

The results of this experiment show great promise. However, there are several limitations that need to be improved upon before continuing this research.

While the current dimensions and weight of the interface along the finger are compact enough for a nearly full range of motion, the next iteration could be even more compact. The initial cable guiding system that was modified for the prototype was that of a Nova development model. The market-available Nova uses an even more compact system that could be modified to include guides for the novel haptic display.

More important is the further development of the actuation module. As of now, this module weighs approximately 250 g which is not yet fit to be mounted on the dorsal side of the hand. With the integration of the display and the Nova in mind, both the weight and dimensions of the actuation module should be reduced considerably, to allow for comfortable use outside of a constrained experimental setting.

Another requirement that needs to be met before moving from a constrained scenario to free motion is the tracking of the x-coordinate of the fingertip, as this still requires a frame-mounted sensor for the current prototype. Additionally, the used potentiometer readings were not compensated for the angle the wire made between the sensor and the fingertip beyond the fact that the sensor was mounted more remotely to reduce this effect. We argue that this effect only had a marginal influence on the results, as both the recorded shape and reproduction of the said shape occur in the same warped plane. Should the interface be included in a full VR setting, optical tracking seems the most promising solution. Systems such as the Pico Neo 4 and Meta Quest 2 already incorporate this technology for their controllers, making it more readily available than alternative solutions.

Should a similar constrained environment test be performed in the future with improved hardware, there are also several limitations regarding the experimental validation that should be considered. First, participants were not fully constrained within the two-dimensional frame that represented the virtual space. Participants were instructed to maintain the same position on the slider and keep their fingers as straight as possible but were not physically prevented from turning or shifting their hands. This could have led to potential changes in the rendered virtual shape, as users may move from the original point on the slider with which calibration was performed. If despite the instructions, a noticeable shift within the virtual space still occurred after a user readjusted their hand, the examiner re-calibrated their new position.

The variety in the shapes that were presented during the experiment was limited, which may have hampered the possibility of making detailed observations regarding device performance for each different shape. Future research should include more diverse and distinct shapes to further identify the capabilities of the haptic display.

If a similar test with this improved hardware shows promise, the next logical step would be to change the environment within which the test is performed. To create even more immersive tests and experiments we could move from a two-dimensional to a three-dimensional space within which the user is not constrained in any way.

Once this is possible, the haptic interface itself could also be improved. As of now, the mobile platform moves in a constrained normal direction with regard to the finger, while being able to rotate along its axis. One could consider the inclusion of another angle of rotation along the platform, to provide not only rolling but also pitching feedback along the fingertip, to further increase immersion in a three-dimensional space.

V. Conclusion

We designed a novel prototype that consists of a novel haptic fingertip display combined with an existing kinesthetic force feedback system. It is compact with a low weight around the fingertip, making multi-finger applications possible. It is remotely driven by a separate actuation module. The display is capable of providing tactile feedback on multiple points along the fingertip and can completely remove contact with the finger when no feedback is required. To evaluate the novel device, a shape exploration and reproduction experiment was performed. Participants were asked to replicate an unseen shape based purely on feedback from the device. We found that the combination of kinesthetic and tactile feedback resulted in better reproduction of these virtual shapes than purely kinesthetic feedback. However, no significant effects on motivation, workload, or time required to explore each shape were found.

We conclude that the combination of tactile and kinesthetic feedback could lead to more realistic and immersive virtual environments and potentially more effective virtual training exercises.

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