FingerFlex: Shape Memory Alloy-based Actuation on Fingers for Kinesthetic Haptic Feedback

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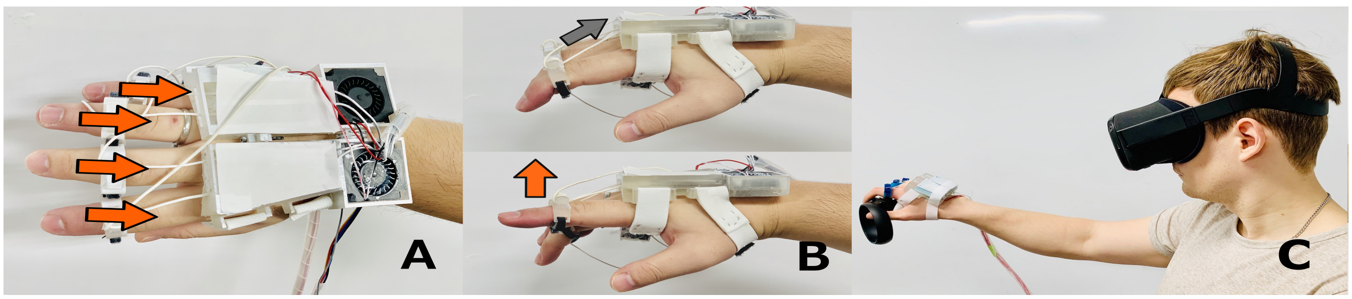

Figure 1: FingerFlex. A: Top view in operation. B:Side view showing the finger before and after actuation. C: User typing a key on a number pad (one of the application scenarios

ABSTRACT

The tactile and kinesthetic sensation of pushing a button is usually lost when interacting with modern devices like touchscreens and/or virtual reality platforms. We present FingerFlex, a standalone glove wearable actuating the metacarpophalangeal joint (MCP) of each finger via shape memory alloy (SMA). SMA actuation is subtle, silent, and light, making it ideal for actuation of the fingers which we use to simulate the sensation of pressing a button.

For our first study, we evaluated the engineering performance of FingerFlex by altering the current and triggering different levels of stimuli to the user's fingers. We show that users can perceive at least 3 levels of actuation with an accuracy of 73%.

For our second study, we found FingerFlex to perform significantly better in terms of input error on a virtual numblock of a keyboard with no significant change in perceived workload.

CCS CONCEPTS

• **Hardware** → **Emerging interfaces**; • **Computer systems organization** → **Embedded hardware**.

KEYWORDS

Subtle haptics; shape memory alloy; kinesthetic feedback; finger actuation

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1 INTRODUCTION

Haptic devices are gaining popularity as an additional feedback mechanism for augmented (AR), mixed (MR), and virtual reality (VR) applications. Haptics can be divided into tactile and kinesthetic feedback [15, 18]. Tactile represents the pressure, vibration, and thermal feedback that we feel with our touch sensory receptors. Kinesthetic feedback, on the other hand, refers to muscle and joint actuation for our perception of weight, linked also to our proprioception [20] and cutaneous feedback [11]. In AR/MR/VR, both tactile [8, 21] and kinesthetic feedback [9] have been explored as some form of hand-worn device or finger-mounted device. Furthermore, some research combines both tactile and kinesthetic feedback

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through haptic surrogates [1, 2]. These solutions are specially tailor-made for virtual environment interactions. In this work, we present FingerFlex, a wearable device that actuates each finger kinesthetically via shape memory alloy (SMA). SMA is a material that can provide tactile sensation via shrinking [3]. For our device, we instead use it as a form of kinesthetic feedback for joint actuation. SMA actuation provides subtle pulls to the joint to imitate the feedback of pressing a button. We use the pulling force from the shrinking of the SMA springs mounted on custom 3D-printed channels to actuate the finger about the metacarpophalangeal (MCP) joint. For virtual applications, we also match the kinesthetic feedback with the visuals of the button actuation to provide a more realistic experience. One issue with SMA is the slow actuation speed (especially after continuous activation), we reduce this problem by using a novel SMA spring and applying active cooling. Still the system is only useful for sporadic activation (every 1-3 seconds) not for tasks like touch typing.

This paper's contributions are the following: (1) We present FingerFlex a wearable haptic device that can actuate finger MCP joints using SMA springs. It is subtle, silent, and light and can simulate the kinesthetics of a single button press. The system schematics and design will be open-sourced [1]. (2) We performed a user study to evaluate user's perception of the actuation. We found that users can distinguish 3 levels of actuation with 73% accuracy. (3) We evaluate the performance of FingerFlex in a VR environment. Users make significantly fewer errors during input on a number pad with FingerFlex than without it.

2 RELATED WORK

Haptic wearable devices have been explored using many different kinds of approaches, either as a wearable [8], or attached to a physical device for additional tactile feedback [14]. In the following, we focus more on wearable approaches, as well as an in-depth look at works using SMA specifically.

Most proposed haptic devices are quite large/heavy. Son et al. [17] developed a haptic glove providing tactile and kinesthetic feedback to the palm and fingers using a servo motor for each finger. The sheer size and weight of it make the device unsuitable for use cases outside of a controlled environment. The closest related work is by Lopes et al. [10] using EMS for haptic sensation for walls and heavy objects. EMS allows joint actuation of the arm, which is why the author focuses on larger-scale feedback as opposed to our implementation that is more fine-tuned for finger haptics.

To our knowledge, there is very little related work regarding the use of SMA for button press haptics at this point of writing. However, SMA is a common material used for soft robotics [16] because of its non-linear actuation that is closer to actual organic movement as opposed to rigid motors and mechanical joints.

Haptic-based research that looks at the usage of SMA can be seen by Suhonen et al. [19], Gupta et al. [5] and Chernyshov et al. [3] who mainly explored its use for squeezing feedback and tactile sensation on the wrist and finger. A more recent related work, Springlets [6], uses SMA springs as an on-skin tactile interface to be used in various scenarios because it is thin, flexible and silent. PhantomTouch [12] and Touch Me Gently [13] used SMA to instead simulate the sensation of touch via shearing forces. These works focus on tactile sensation as opposed to kinesthetic feedback.

[1]url blinded for review

3 FINGERFLEX PROTOTYPE

FingerFlex uses 3D printed parts as well as Velcro for ease of attachment to the hand. The housing for the prototype is 3D printed. The finger joints are fixed to the FingerFlex prototype using also small Velcro rings connected to the SMA springs over strings. The velcro and the length of the strings leading to the SMA spring can be easily adjusted for each person (accommodating fro anthropometric differences in user hands see 1). The SMA actuation provides a resistive kinesthetic actuation, with a gradual increase in pulling force as the finger approaches the contact point for a haptic sensation. We implemented a single button press for our evaluation, yet different and combined actuations are also possible. Instead of an SMA wire, our initial testing shows that a spring-shaped SMA is able to generate a larger, faster pull with a higher recovery force. Four SMA springs[2] (excluding the thumb) are attached over strings to each finger to pull them backwards. We use tensile springs with a mean diameter of 5mm, a wire diameter of 0.8mm, and a maximum compression force of up to 3N. The typical force is a maximum of 30(N). The SMA springs work from an approximate temperature of 45degree. We need to limit activation time to maximum 7 seconds (crucial to not increase the temperature over 70degree). The spring changes its contraction speed depending on the temperature, it exhibits maximum contraction within approximately 1.5 sec. For a button-press illusion the feeling is pretty instantaneous (under 300 ms). Yet, it takes about 500 ms to cool the spring down again for another activation. This time gets longer the more often the system is used and is a limitation of FingerFlex. The prototype will not work for touch typing or other applications that require fast feedback.

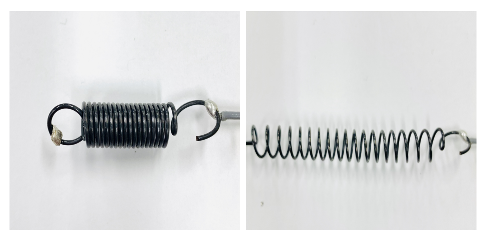

Figure 2: The compressed SMA spring when heated (on the left), the SMA spring at room temperature

The outer frame is designed according to the shape of the hand and shields the hand from the thermal properties of the SMA springs (heating up to 40-50degree for short periods of time (max 3 sec.). Longer tests didn't show an increase in temperature on the bottom of the 3D printed frame. The SMA springs are placed in a frame designed at 6.5cm so that it operates within the range of 1 to 6cm when it is contracted. We designed a custom printed circuit board (PCB). The prototype is only for the right hand, with the Velcro ring connections extending from each of the SMA springs. **Software -**

[2] https://www.saesgetters.com/products-functions/products/shape-memory-alloys-nitinol

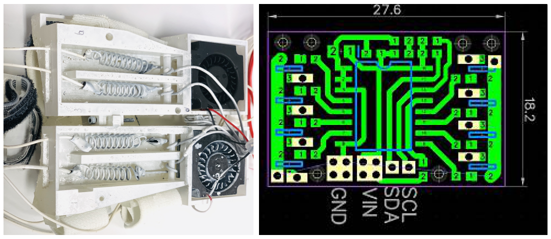

Figure 3: Glove Module with mounted springs and cooling fans(left)PCB board(Right)

The software uses the Unity Engine for the VR visualization and PCB serial connection. The system is connected to a desktop PC and controls the SMA springs via Unity and Arduino. The tension of the SMA spring depends on the time and amount of the current. For FingerFlex, the tactile sensation is activated in the range of 0.8-1.6N. The sense of force is presented only max up to 7 seconds, as prolonged activation may break the SMA springs due to overheating.

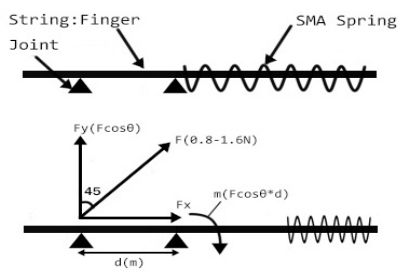

Figure 4: Rotation Force Moment Diagram

Kinesthetic Joint Actuation- The SMA springs are mounted at the back of the gloves to pull each finger individually via a string that is attached to the proximal at theta = 45 degree. This causes the rotational point to be at about the MCP joint, with the generated torque being equivalent to Fcos theta*d. The distance d refers to the length of the proximal bone which is different for each finger as well as between gender, ethnicity and various factors [4]. Our initial measurements range between 0.045m to 0.056m. With the pulling force F between 0.8N and 1.6N, the generated torque is equivalent to a range between 0.025Nm and 0.063Nm. We illustrate this in the moment diagram shown in Figure 4. A possible drawback regarding SMA-based actuation is that the response can potentially be slower after several actuations due to the high residual temperature. To combat this, we introduce cooling fans for our prototype.

The airflow from the fans are piped through 3D printed lanes which also houses the SMA springs. We use the BFB03505HHA-A cooling fans manufactured by Delta Electronics[3] with a maximum speed of 8500 RPM and a power rating of 750mW. Future prototypes can be improved using water/liquid cooling.

[3] https://www.mouser.com/manufacturer/delta-electronics/

4 STUDY 1: FINGERFLEX PERFORMANCE

This study is to investigate the user's ability to differentiate and recognize between several levels of stimuli from the SMA. Before initiating the main study, we first conducted a pilot study to determine the minimum threshold where a user can feel the actuation from the SMA for each finger. We recruited 5 participants (3 male) between the age of 20 to 30 (mean: 24.3, std = 0). We then gradually increase the amount of current that flows into the device. We found that users start to perceive the actuation at (2.2V,2.43A), with an actuation force of 0.8N. Therefore for our user study, we begin actuation with 0.8N. We recruited 16 participants (12 males and 4 Females) between the ages of 23 to 28 (mean: 24.8). They were also asked to sign a consent form stating that at anytime, they may withdraw from the experiment if they wish to do so. We performed the experiment using a single glove that actuates the 4 fingers. A desktop computer was used to run the Unity which instead was used to control the prototype.

Experimental Design and Procedure- The level of each stimuli was designed to be maintained within the range of comfort and not too exerting, which should range between the result of the pilot study of 0.3N to 4.8N [7]. For 3 granularity levels, the applied stimulus are 0.8N, 1.2N and 1.6N. We apply the same stimuli for all the fingers at the same time. Each participant was first informed about the goal and nature of the study (also stated in the consent form). They were then outfitted with the glove. The procedure is divided based on the previously assigned granularity level, with a training and testing phase. The participant experiences the 3 levels of stimuli in an increasing order. Then, they enter the testing phase, where a random stimuli from the corresponding granularity level was activated. The participant needs to select which of the stimuli level they think they experienced. This is repeated 5 times, where the stimulus was randomly activated (for three levels of granularity, a total of 5 x 3 = 15 trials in random order was tested on the participant).

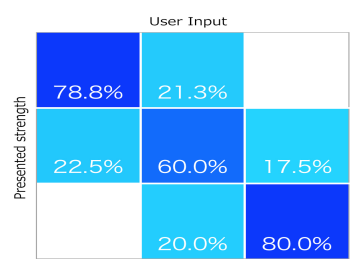

Figure 5: Study 1 Result, Confusion Matrix

Results and Discussion- Figure 5 shows the overall accuracy for the perception of force feedback by our device. Participants were able to discriminate between 3 different strength levels with an average 73 % accuracy. As seen from the confusion matrix, errors happen just between adjacent levels. The applied force of 1.2N (Level 2) seem to elicit the lowest accuracy when compared to 0.8N (Level 1) and 1.6N (Level 3). It can also be observed that for Level 1, 21.3% perceived it to be level 2, whereas for Level 3, 20% perceived it to be level 2. This is understandable because the lowest induced force of 0.8N is the minimum perceivable force during our pilot study and is easily distinguishable from higher forces, whereas the highest induced force of 1.6N actuates the finger the furthest, allowing one to easily perceive it. For Level 2, more participants perceived it to be Level 1 (22.5%) compared to Level 3 (17.5%), though not by a large margin. We believe this is attributed to Level 3 being more perceivable than Level 1, which can also be seen on its achieved accuracy (80% versus 78.8%). As expected, there were no participants who perceived Level 1 as Level 3, and vice versa.

5 STUDY 2: BUTTON PRESS FEEDBACK

For our second study, we evaluated the virtual button press performance as well as perceived workload when using FingerFlex. We chose keypad input because, it is one of the most common interface that requires buttons and exists as a physical device, on touch screen devices, and even AR/MR/VR environments. We recruited

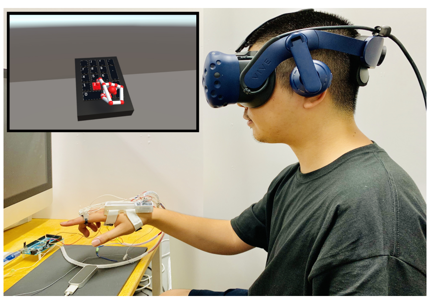

Figure 6: The study setup : Evaluating SMA springs with Input test In Virtual Reality Environment

the same 16 participants from the previous study to participate in this study. Information regarding the second study was already included in the consent form that they previously signed.A desktop computer was used to run the Unity game engine which instead was used to control the prototype. For finger tracking, we use a Leap Motion sensor.

This experiment is also a within-subject study to obtain feedback regarding input performance and perceived workload when using FingerFlex. We chose to use a VR environment for the input task as we can easily manipulate the complete visual experience of the participants (see Figure 8). We used a simplified virtual number pad to allow single handed use. The first scenario is simply keypad input on the virtual number pad with 2 patterns. The key have been activated 2 or 4 seconds for each scenario. And then totally 1 minute (2 seconds*30 times) and 2 minutes (4 seconds*30 times) using our predefined number as the baseline. The seconds scenario then requires the user to wear our prototype and repeat the same task using a progressively increasing haptic sensation the more the finger presses into the button. For all scenarios, each key lights up during activation and deepening of the key during actuation is reflected on the virtual number pad. The order of the scenario was counterbalanced to negate ordering effects.

At the end of the study, each user verbally reports their experience openly, as well as answering the provided immersion questionnaire.

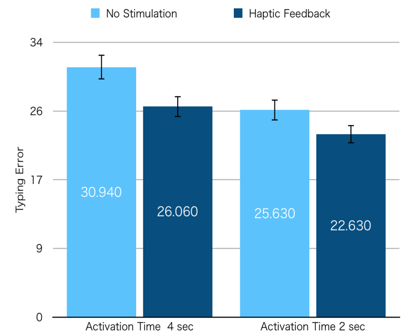

Figure 7: Study Result: The Score of Input Error

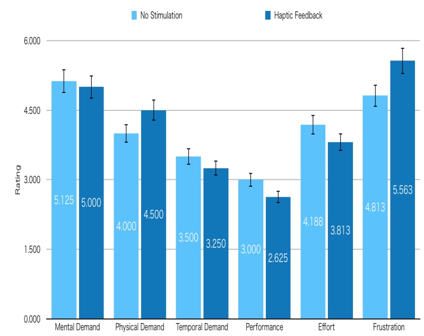

Figure 8: Nasa TLX plot

Results and Discussion. As shown in Figure 7, the mean Input Error for the 4 seconds no-stimulation condition is 30.95 (SD:6.923) without haptic feedback and 26.06 (SD: 6.628) with haptic feedback; For the two second condition 25.63(SD:8.180) without and 22.63(SD:7.641)with the haptic feedback. Applying a t-test shows significant differences within the activation time of 4 seconds.($t = 3.917, df = 15, p < .05$). No significant difference was confirmed of the activation 2 seconds ($t = 1.695, df = 15, p > .05$). Many users reported confusion in the use case without haptic feedback, as they were not sure if the button was pressed or not (leading to missed presses or multiple presses). Tactile stimulus feedback is provided to the user at a fixed value of 1.2N. The Nasa TLX does not show a significant difference in perceived workload index. The users perform better in the 4 sec. activation interval, yet don't feel as if they do.

6 CONCLUSION AND FUTURE WORK

We present FingerFlex, a haptic wearable glove that can actuate the MCP joint and provide kinesthetic feedback. We evaluated the system in a sensitivity study and showed that it can be used for haptic feedback in a number input task. Users with FingerFlex make significant less errors during input.

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