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Assessment of Multi Vibrotactile-Skin Stretch (MuViSS) Haptic Device to restore sensory feedback in upper limb amputees using prosthetics

Andrea Campanelli¹, Charl lie Saudrais², S bastien Mick², Monica Tiboni¹, Fabien Verit ² and Nathana l Jarrass ²

Abstract—This study explores the MuViSS (Multi Vibrotactile - Skin Stretch) haptic device designed to enhance cognitive processes and behavior through sensory feedback in upper limb prosthetics. The device employs feedback that combines the stretching of the skin in conjunction with proprioception and cue alerts upon contact. Our previous work involving nine non-disabled participants wearing the MuViSS and controlling a modified prosthetic hand demonstrated its efficacy compared to traditional vibration force feedback and a no-haptic condition. Preliminary experiments with an amputated participant have been performed to further support the efficacy of MuViSS in providing valuable sensory feedback. Positive results from these preliminary experiments confirm the potential of the MuViSS device and its feedback strategy to improve control and user experience in the field of upper-limb prosthetics.

I. INTRODUCTION

Nowadays, upper limb prosthetic technology mostly involves myoelectric prostheses, which are controlled using electromyographic signals from residual limb muscles [1]. While they offer a natural appearance and enhanced functionality, they fail to address the persistent challenge of the somatosensory system’s lack of information. The myoelectric control has, in fact, heightened this issue, despite the overall improvements in comfort and functionality [2], [3].

Upper limb prosthesis users have a strong demand for sensory feedback [4]. Cordella *et al.* [5] reported that sensory feedback is widely considered a priority for prosthesis users because it plays a fundamental role in our cognitive processes, emotional state, and behavior. Furthermore, in a study on lower limb loss by Raspopovic *et al.* [6], it was found that neural sensory feedback through stimulation electrodes led to increased walking speed and self-reported confidence, along with reduced mental and physical fatigue, compared to trials without stimulation in lower limb amputated participants.

However, commercial arm prosthetic devices, such as those from Ottobock and  ssur, often lack the necessary sensory feedback to support effective sensorimotor looping. In the absence of feedback, the patient must learn compensatory strategies: use of visual feedback, unconscious use of acoustic feedback from interaction with the environment (sounds of motors, gears under load, or deformations of the environment). The slowness and attention required for this sensory integration make the use of the prosthesis complex and cognitively heavy [7]. By providing sensory information,

tactile feedback can help create a more natural and intuitive experience for the user and reduce the cognitive load required to control the prosthesis.

A variety of physical parameters can be measured using different types of sensors, such as force, finger position (angle), slip, and temperature. Typical information provided in studies with sensory feedback includes proprioception and interaction forces [8]. Proprioception allows the users to perceive the position and orientation of the prosthesis, while interaction force refers to the force exerted by the user and experienced through the prosthesis during interaction with objects or surfaces. Heidi *et al.* [9] combined both types of information and attempted to provide additional stiffness information. However, studies have also examined the impact of providing haptic feedback information on the texture [10], shape recognition [11], and contact cues [12].

After this information is collected, it is processed and analyzed before being used to generate feedback. The tactile feedback generated is directed to a specific part of the user’s body that is able to detect and interpret the tactile information. Various modalities to provide adequate haptic stimulations have been explored over the years. Non-invasive methods use external devices that provide tactile feedback to the user on the skin or other body parts, eliminating the need for surgical intervention and reducing invasiveness and associated risks. Typical non-invasive methods include vibrotactile feedback [12], electrotactile feedback [13], and mechanotactile feedback [14] (*e.g.*, skin stretch, pressure, and squeeze).

A. Related works

An example of a mechanotactile device is the HapPro [14], which has been integrated into the SOftHand Pro, an anthropomorphic robotic hand [15]. It uses proprioception information about the opening/closing position of the hand obtained from encoders in the motors. The haptic device allows a carriage to slide linearly over the skin of the forearm, giving the user of the prosthetic hand the sensation of the grasped object’s size. Experiments conducted by the authors evaluated the device’s performance in grasping balls and cylinders of various sizes and demonstrated its ability to provide accurate and reliable proprioceptive feedback. Another notable haptic device is the Haptic Rocker [16], [17], which uses the rotational stretch of the skin to convey valuable information about the size of objects to be grasped.

Vibrotactile feedback has been extensively explored for force feedback applications where vibro motors are brought

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into contact with the skin, as in the work of Nabeel *et al.* [18], which uses an Eccentric Rotating Mass (ERM) vibro motor. A classic example is the VF-M system [19] (vibrotactile frequency modulation), which uses dual-frequency vibrotactile stimulation to restore the perception of strength and stiffness in individuals with sensory impairments. The device conveys information to the wearer that is proportional to the force applied to the corresponding fingertip.

Typically, a proportional force feedback problem arises from the position control of commercial hand prostheses. Due to the high finger velocity, it is challenging for users to control and modulate the applied force. To overcome this problem, Clemente *et al.* [12] developed a device that taps into established sensorimotor mechanisms to provide brief sensory cues instead of continuous feedback, using vibrotactile stimuli. This device provides feedback when a prosthetic hand makes and releases contact with objects, events that are important for natural grasping and lifting control.

Notable results have been also achieved using electro-tactile stimulation, providing both proprioception and grasping force information [13], [20], demonstrating improvements in prosthesis control, modulating force identifying physical characteristics of different objects.

Recent advancements have led to the development of haptic devices capable of reproducing diverse skin sensations using various tactile actuators. This multi-actuator approach enhances information richness compared to single-actuator systems, broadening the range of stimuli alignable with prosthetic hand stimulation. However, maintaining a simple sensory feedback system is crucial to prevent cognitive overload when interpreting perceived sensations. An example of a wearable, multisensory haptic feedback system is Tasbi [21], which provides both vibrotactile and squeeze feedback functions. A different device targeted to upper limb prostheses is presented by Clemente *et al.* in [22]. It conveys information to the individual about the contact between the fingers and the environment through a vibrotactile stimulus and the grasping force exerted by the prosthesis on objects through force/pressure feedback.

Our previous work [23] presented the MuViSS (Multi Vibrotactile - Skin Stretch), an innovative multi-modality feedback system, accompanied by a new device capable of delivering haptic sensory substitution. The experiments on nine non-amputee subjects showed that the new feedback solution was able to provide size and stiffness information in the absence of vision. In addition, the feedback improved the performance of a motor task, specifically grasping a marble, with vision. This study further investigates this sensory feedback system on an amputee subject who has years of experience using the prostheses without any sensory feedback information received.

II. MATERIAL AND METHODS

The MuViSS (Multi Vibrotactile and Skin Stretch) has two different types of tactile feedback: skin stretch and vibrotactile sensations. It can be worn either on the residual

limb or on the opposite arm, depending on the level of amputation.

The MuViSS is designed in conjunction with a poly-digital prosthetic hand (from Taska Prosthetics) to provide continuous, valuable tactile feedback to prosthesis wearers with simplicity and comfort in mind. The sensor-equipped Taska hand collects data about its movements and interaction forces and transmits this sensory information to the MuViSS haptic device, which translates it into tactile stimuli.

A. The MuViSS Haptic Device

The MuViSS haptic device is composed of three different types of stimuli:

- The stretching of the skin: the module is placed on the upper part of the forearm. The linear motion of a designed spherical factor is generated by a small servomotor (SERVO DMS-MG90-A), a rack and pinion system. The factor has a linear range of 3 cm, which corresponds to a spatial rotation of the motor of 180°. The structure of this module is shown in Figure 1.
- The vibration of an ERM: the ERM motor, a 10mm diameter vibration motor, is attached directly to the bottom of the housing, which contains the control board (Arduino MKR1010) made of an elastic material. The ERM comes into contact with the skin on the lower part of the forearm or wrist.
- The vibration of two LRAs (Linear Resonant Actuators): the two LRA modules consist of a 3D-printed part that acts as a buckle and contains the motor (C12-003 from Microdrives) and its driver. The modules can slide along the elastic band and let the motor apply normal pressure to the arm. They are placed on the left and right side of the wrist or forearm.

All modules and the housing of the control board are connected with two elastic nylon straps that can be fastened with Velcro. The assembly of the entire MuViSS is shown in Figure 2, and the stimuli locations when the device is worn are shown in Figure 3.

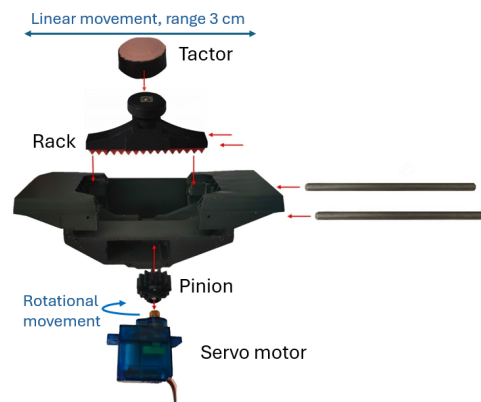


Fig. 1. Scheme of the assemblage of the skin stretch module.

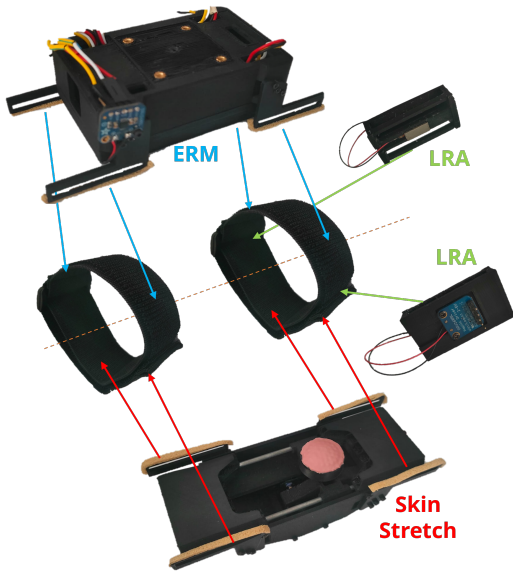


Fig. 2. Scheme of the assemblage of the MuViSS.

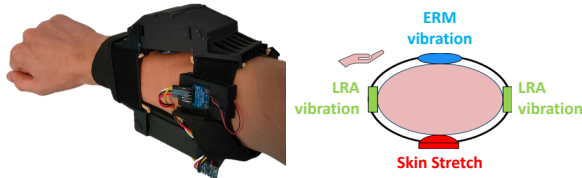


Fig. 3. MuViSS worn by a person on the left. Scheme of stimuli placement on the right.

B. Integration of MuViSS with the Taska hand

The setup utilized a commercially available Taska hand, a myoelectric robotic hand with interchangeable joints and wrist, compatible with various in-hand controller terminals. Additional sensors and an electronic acquisition unit (Arduino MKR1010) were added to gather data for MuViSS. Two Flexiforce sensors and a rotary potentiometer were integrated, with custom 3D-printed fingertip attachments accommodating the force sensors. These sensors were strategically placed in the thumb and index fingertips. The potentiometer, measuring hand openness, was mounted using two 3D-printed parts. The first part secured the potentiometer, while the second, inserted into the index finger, facilitated rotation. A custom 3D-printed enclosure housed all electronics for sensor power and control. Figure 4 depicts the final modified Taska hand setup, showcasing the integrated components.

C. System control algorithm

Two circuits were developed, one for the hand prosthesis and one for the MuViSS. Wireless communication is used to transmit the measurement data from the Arduino on the hand to the Arduino in the haptic device.

The presented feedback strategy combines two stimuli, based on both proprioception and contact information. We call it PC feedback, where P stands for proprioception and C for contacts. Proprioception information is captured by the

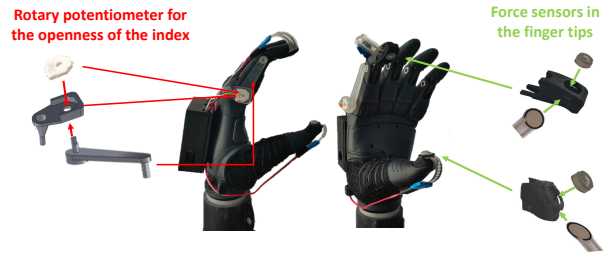


Fig. 4. Instrumented Taska hand.

potentiometer and rendered to the user via the skin stretching device. A second-order low-pass filter with cutoff frequency equal to 2.5 Hz was developed to reduce the noise of the measurement. Contact information is detected using force sensors. A contact is detected when the force exceeds a predetermined threshold. A second-order low-pass filter with cutoff frequency equal to 13 Hz has been designed to reduce the noise of the measurement. To relay this information to the user, the LRA generates a vibration pulse of 300 ms. If the contact duration is shorter, the vibration also lasts a correspondingly shorter time. Each LRA is associated with a specific fingertip and sensor, allowing for localized feedback. Isolated studies [12] have shown that the implementation of contact information alone has led to performance improvements.

Each channel of the MuViSS can be used also singularly, since they are not dependent on each other. We call the C feedback the strategy that involves only the contact feedback of the PC.

The ERM module was included for the previous experiments performed on non-amputee subjects [23], but can also be used to try new feedback modalities.

III. PROTOCOL TO MEASURE MUVISS'S IMPACT ON PROSTHESIS USE

The feedback experiments with the prosthetic hand aim to assess feedback effectiveness in everyday activities. The study involves two tasks: a recognition task comparing the impact of PC feedback and without haptic feedback (WF) on size and stiffness discrimination, and a motor task testing performance with PC feedback mechanisms, with only contact (C) feedback and WF during dynamic everyday activities. Task order was randomized, and a person with right forearm agnesia participated in both tasks, wearing the MuViSS device on the forearm of the healthy arm, as depicted in Figure 5. After each condition, the participant filled out a NASA-TLX questionnaire to evaluate perceived workload. MuViSS was worn on the wrist during both experiments.

A. Recognition task

The participant, blindfolded to eliminate visual influences, interacted with a prosthesis in a haptic task. The task included spheres of varying sizes (20, 35 and 50 mm) and stiffness levels (rigid wood "approx. ∞ ", 1, 3 N/m) attached to a fixed base. The participant used the prosthetic hand to



Fig. 5. Upper-arm amputee participant wearing the MuViSS.

determine the level of size or stiffness during the specific task.

Size and stiffness recognition tasks were performed separately in randomized order during different sessions. Both size and stiffness recognition were divided in three phases:

- the training phase, where each condition was observed once with open eyes;
- the reinforcement phase, where the blindfolded participant had to determine size or stiffness of nine random spheres, and after his choice, the correct answer was provided;
- the testing phase, where the blindfolded participant had to determine size or stiffness of nine random spheres, and the participant's answers were collected. Each session comprised fifteen trials (five for each sphere), as illustrated in Figure 6.

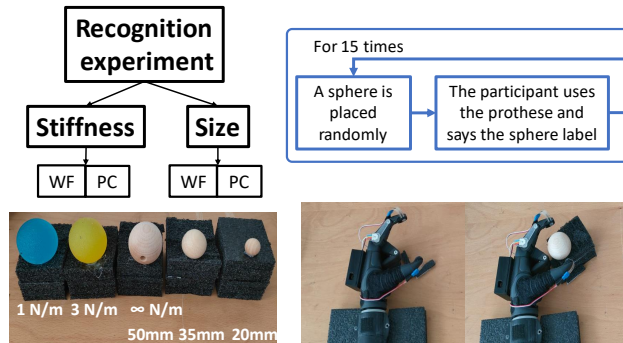


Fig. 6. Setup of the recognition experiment, using Proprioception Contact Feedback (PC) and Without Haptic Feedback (WF).

Throughout the experiment, the participant went through

each of the previously described conditions, resulting in a total of four recognition phases: WF and PC for stiffness and size.

B. Motor task

The participant sat on a fixed chair facing a table with a box divided in two compartment. One compartment held a marble on a support, while the other remained empty. To add complexity and introduce variability, two types of marbles, one wood and one hard plastic, were alternated in each trial. In total, the participant moved 14 marbles in each condition, 7 of each type. Refer to Figure 7 for a visual representation of the setup.



Fig. 7. Setup of the motor experiment, using Without Feedback (WF), Proprioception Contact Feedback (PC) and Contact Feedback (C).

Before each condition (PC, C, WF), the participant had one minute to familiarize themselves with the prosthesis and MuViSS, moving the marbles from one compartment of the box to the other. Following the release of each marble, the participant had to fully open the hand before attempting the next grasp. If a marble fell during grasping, the participant restarted by fully opening the hand again. The order of feedback conditions was randomly determined and distributed. The participant was aware of being evaluated based on time and force applied.

During each trial, data from force sensors and the encoder were recorded. The value of force for a trial was calculated as the maximum average force between sensors during marble grasping, while the value of time was measured as the interval between closure onset and marble release.

IV. PRELIMINARY EXPERIMENTS ON A AMPUTATED PARTICIPANT

This session had the aim to firstly explore the experience of sensory feedback by a participant that never tried it and investigate the PC feedback with a prosthesis controlled through EMG signals.

The participant undertook the recognition task exploring the WF and PC feedback strategies. The results are presented in the form of confusion matrices in Figure 8. In terms of size recognition, the confusion matrix accuracy was 67% for WF and 87% for PC, while in stiffness, the confusion matrix accuracy was 47% for WF and 67% for PC.

Afterwards, the participant undertook the motor task exploring the WF, PC and C feedback strategies. The latter modality has been consequently tested because during the trials, the participant consistently expressed concern that the skin stretch feedback was too powerful and nearly overshadowing the sensation of vibration, a phenomenon not

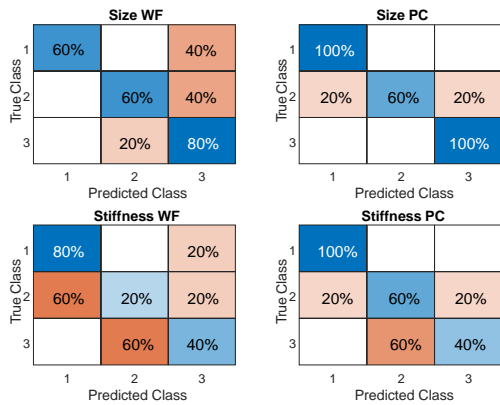


Fig. 8. Confusion matrix results of the recognition experiment with a amputated participant using PC and WF Feedback.

observed in non-amputee participants in the previous work [23]. This discrepancy may be attributed to variations in the participant’s skin sensitivity, leading to diverse perceptions of stimuli.

During grasping, the average force values for the six trials were: $WF = 3.73 \pm 0.61Nm$; $PC = 3.24 \pm 0.73Nm$; $C = 3.10 \pm 1.22Nm$. Considering the time, the average value of time between the 6 trials during the grasping are respectively: $WF = 7.784 \pm 2.648s$; $PC = 7.280 \pm 1.285s$; $C = 6.710 \pm 1.081s$. Time and force average values are displayed in Figure 9. At the end of the motor task, the participant compiled the NASA-TLX survey, shown in figure 10.

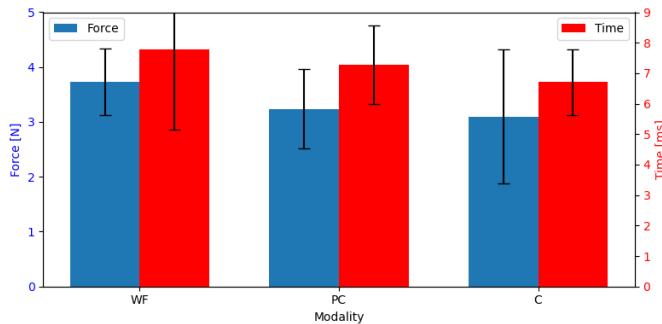


Fig. 9. Average results comparison of the three feedback with a amputated participant, where WF is without feedback, PC is proprioception and contact feedback and C is the contact feedback.

V. DISCUSSION

The experiments focused on PC feedback, building on previous studies with non-amputee participants that highlighted its potential compared to force vibrotactile feedback [23]. This time, the primary comparison is between the PC and WF modalities, since the subject has always used the prosthesis without any haptic feedback.

In size recognition, PC yielded better results with a high accuracy, indicating the effectiveness of the skin stretch channel. Although WF had a lower accuracy compared to PC, the result cannot be considered entirely random and might be influenced by auditory cues or mechanical

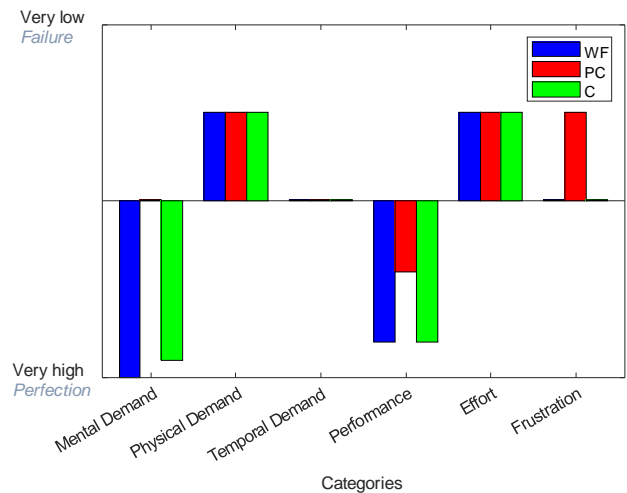


Fig. 10. Surveys results in motor experiments with a amputated participant. For all the categories, small values indicate better results.

transmission of contact. In stiffness recognition, while PC achieved better results, they were not as good as in size recognition. A first reason is related to the soft feeling of vibrations compared to skin stretch. Moreover, despite of the prosthetic device used in the previous work [23], the participant could regulate the closing velocity of the hand, changing the sensations produced by the MuViSS with the different trials, and complicating the recognition while using high speed. Overall, the introduction of the feedback let the participant complete recognition task with better results compared to WF.

Regarding the motor task, introducing feedback reduced applied force on average, but the standard deviation increased, with occasional force sensor saturation, especially with WF. Moreover, the introduction of the feedback reduces the time spent to complete the task. Considering the surveys, there were no differences in physical demand, temporal demand, and effort. WF required less mental demand, probably because the participant is more familiar with this strategy. PC yielded the worst results: the participant reported repeatedly that the contact force generated by the skin stretch was too strong. He rated the C modality similarly to the WF modality, even if it was the first time he was trying it. Regarding expected performance and frustration, WF and C were rated equally, while PC was rated worse than both.

The introduction of the feedback led to better results: in C condition, the participant performed slightly better than in PC condition, probably because the skin stretch felt unpleasant and eclipsed the vibro-tactile feedback. Additionally, a distinction arose in the difficulty of controlling the device. Operating with EMG required concentration and effort from the amputated person, whereas button-based control used by non-disabled participants was straightforward and infallible [23]. This suggests that the complexity of multiple information channels and modalities might pose a challenge in terms of cognitive load.

Although skin stretch proved essential for recognition tasks like size and stiffness, its necessity diminished in a motor task where vision was unobstructed. Despite its role in recognition, the participant favored the simplicity of contact information alone in the motor task. However the results showed that PC is still improving the performance compared to WF, and can provide useful information in more contexts. Surely, more tests conducted with different participants, need to be done to investigate the efficacy in non-disabled participants, focusing on the haptic sensations provided together with the mental demand required to control the prostheses.

VI. CONCLUSIONS

This study explores the potential of MuViSS, a wearable multimodal haptic device, and the PC sensory feedback strategy on an amputee subject.

First preliminary experiments confirm the importance of sensory feedback and show some first positive results on the MuViSS device and PC feedback strategy. Further experiments on amputee subjects will be performed to investigate the role of the proprioception in motor tasks, to improve the feedback sensation and understand deeper the potential of the feedback PC and the MuViSS haptic device in other everyday tasks.

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