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Auditory Display as a Prosthetic Hand Sensory Feedback for Reaching and Grasping Tasks

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Abstract— **Upper limb amputees have to rely extensively on visual feedback in order to monitor and manipulate successfully their prosthetic device. This situation leads to high consciousness burden, which generates fatigue and frustration. Therefore, in order to enhance motor-sensory performance and awareness, an auditory display was used as a sensory feedback system for the prosthetic hand's spatio-temporal and force information in a complete reaching and grasping setting. The main objective of this study was to explore the effects of using the auditory display to monitor the prosthetic hand during a complete reaching and grasping motion. The results presented in this paper point out that the usage of an auditory display to monitor and control a robot hand improves the temporal and grasping performance greatly, while reducing mental effort and improving their confidence.**

I. INTRODUCTION

It is well known that upper limb amputees have to rely extensively on visual feedback in order to monitor and manipulate successfully their prosthetic device. This situation seems to lead to a high conscious burden for the users, which generates fatigue and frustration [1]. This lack of sensory feedback is a major drawback that many researchers are trying to cope with by using indirect methods to convey information from the artificial limb to the amputee, such as electro-cutaneous stimulation [2], vibrotactile stimulation [3], and force stimulation [4]. These systems are aimed to improve motivation, lower the cognitive burden, accelerate adaptation to the body schema, and to allow amputees to feel the prosthetic device as part of their body. However, these systems have limited resolution, only simple patterns can be conveyed, are difficult to setup, and it is difficult to learn and understand the meaning of the stimulation. Also, there are problems with comfort and rapid habituation to the stimulation, which don't allow the user to differentiate between patterns after a long exposure.

On a different approach, auditory cues have been also used to convey texture information from the prosthetic hand to its user [5]. However, no kinesthetic or force information was transferred to the amputee, which limits its usability. Furthermore, the results obtained in these studies are very positive, but most of them focused on conveying only tactile information to improve grasping, not taking in consideration the reaching phase of the motion. Also, the usability and advantages of these feedback methods were explored mainly by only looking at the performance results, which do not take into account measurements of the user's mental effort, attention, and emotions. Auditory feedback has been also used for neuromotor rehabilitation therapies [6-8], and has played a major role for the analysis and understanding of multiple variables simultaneously in human-computer interfaces [9].

Our research team has developed an auditory display scheme to improve performance in prosthetic hand manipulation tasks. The results showed how performance was greatly improved, while reducing mental effort when the auditory display was used with a real prosthetic hand [10]. However, so far the system was used in a static setting (similarly to other studies), thus the effect of this sensory feedback system in a whole reaching and grasping dynamics wasn't explored. Therefore, the main objective of this study was to explore the effects of using the auditory display to monitor the prosthetic hand during a complete reaching and grasping motion. This study is a step closer to design a complete multivariate sensory feedback system that could be used as a training or control support for prosthetic limb applications. For this study we focused on temporal and grasping performance when using a prosthetic hand. Also, the NASA TLX and the Self-Assessment Manikin questionnaire were used and the subject's Electrooculogram (EOG), electrocardiogram (ECG), electro dermal activity (EDA), and respiration rate were measured in order to assess mental effort, attentional demands and emotions.

II. METHODOLOGY

A. Prosthetic Hand Control

A tendon driven robot hand was mounted on a special socket, as can be seen from Fig. 1. A total of 10 motors were used to control the robot hand, and the robot hand was fitted with 3 bending sensors (Abrams Gentile Entertainment) for the Thumb, Index and Middle fingers, which measured 1 degree of freedom of the rotational angle from the base of each of the finger. Also, force sensors (Inaba Rubber) were used to measure the force excerpted in the Thumb, and Index finger when grasping an object.

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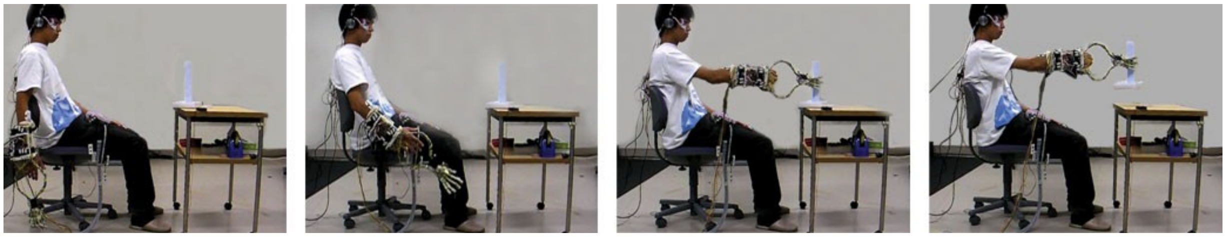

Figure 1. Reaching and grasping movement. The subject starts reaching towards the cylinder and should monitor the robot hand fingers to avoid errors. During the grasping phase he has to control the grip force using an EMG interface. He should apply the minimum force required to lift the cylinder.

In order to control the finger motion pattern of the robot hand during reaching a 10 camera Motion Tracking System (OptiTrack) was used to determine the location of the robot hand in space at a sampling rate of 100Hz. According to the position robot hand position in space and the selected type of grasping, the robot hand was assigned a sequence of fixed hand configuration. For this study only 1 grasping type was used: the palmar grasp. Therefore, the robot hand started from a fully closed position (fist) and while moving towards the cylinder the hand opened until it reached a configuration that could enclose the cylinder. Once the robot hand made contact with the cylinder, the subjects were required to control the prosthetic hand grip by a 2 EMG sensors (Shikikou Engineering) placed in the extensor carpi radialis longus and flexor carpi ulnaris muscles. By making a fast closing motion, the subject was able to instruct the robot hand to close (Grasp Command) at a fix speed of 0.3°/s. Similarly, by doing a fast opening motion the subject was able to instruct the robot hand to open (Release command) at the same speed, and by relaxing his hand he could make the robot hand stop moving. This way the subjects were able to control the grip force applied to the cylinder. The EMG signal was classified after the raw signals were filtered using a low pass filter (50Hz), then rectified and smoothen using a moving average window filter of 100 points.

B. Auditory Display

For this study, the hand motion was discretized into 8 hand configurations, which were represented by different Piano major triads for the palmar grasp. Hand Configuration 1 (C1) was considered to be the state when all the robot hand's fingers were extended and was represented by a low C major triad. Hand Configuration 8 (C8) denoted the state when all the fingers were completely flexed and was represented by a high C major triad. Therefore, the auditory display will present the triads, for a normal reaching motion, as: C_{high}, B, A, G, F, E, D, C_{low}, D major triads. While reaching the system compares the sensor data from the fingers with their fixed trajectory, if the difference is higher than a set threshold it generates an error signal. This error signal is then display as an auditory icon. Auditory icons are representations discrete events with everyday sounds [9]. In this study 3 different auditory icons were used to identify errors in the Thumb, Index or Middle finger.

Furthermore, the robot hand's grip force was directly mapped to the sound of a Cello. This mapping is also a discrete one, but since a very high resolution was used, the subjects perceived a continuous sound. OpenAL API (Creative Labs) was used to playback the sounds.

C. Experiment Settings

8 male subjects, between 22 and 28 years old, right handed, and with no sensory or motor impairment participated in this study. They were asked to come for 2 consecutive days. On the first day the experiment objective, tasks, and experiment setting was explained. After agreeing to participate in the experiment, they were asked to sign an informed consent. Then, they completed a 30 minutes guided training. On the second day each subject was tested in 2 different modalities: Visual Feedback only control (VF) and Audiovisual Feedback control (AVF). For each modality they were asked to perform 10 trials. 10 trials were chosen to reduce fatigue effects since each modality test lasted around 10 minutes. Also, before each modality test the subjects were asked to relax while listening to classical music for 3 minutes, in order to obtain a baseline for the psychophysiological measurements, and between modalities a rest of 5 minutes was held. Furthermore, the order of presentation of the modalities was alternated between subjects. At the end of each test, the subject had to fill the NASA TLX questionnaire and the Self-Assessment Manikin scale.

On the day of the test, the subjects were fitted with all the electrodes to measure the different physiological variables (EOG, ECG, EDA, EMG). Then, they were asked to wear the prosthetic hand and sit comfortably in a chair. The targeted object, a 2 grams cylinder, was positioned on a table at the maximum length of the subject's arm plus the prosthetic hand. Also, they were told to move as little as possible during the trials. Although all 5 fingers moved, they were told that only the Thumb, Index, and Middle finger were going to be tested during the reaching phase.

During the reaching phase, the experiment task consisted of moving the robot hand towards the cylinder (reaching phase) while monitoring whether one of the fingers stopped moving or not since the experimenter forced one of the fingers (Thumb, Index finger, or Middle finger) to stop moving randomly for 5 of the 10 trials. After detecting that one of the fingers stopped moving, the subject was required to stop the arm motion, move their arm backwards to make the robot hand return to the last hand configuration before the error, and then continue with the reaching motion. In this study, only 1 error per trial was presented and only when the hand was moving towards the object. In the VF modality, the subjects could only rely on his vision to monitor the robot hand, which is the current way prosthetic hands have to be manipulated. During the grasping phase, the subjects had to grasp the cylinder by activating the Grasp command using the EMG interface. The subjects were told that they should make the least amount of effort to grasp and lift the object, thus the subjects had to determine when the grip force was enough by using his vision in the VF modality or using the audio along with his vision in the AVF modality. After, they had to lift the cylinder and put it back on the table, then proceed to make the Release command. If the force exerted in the cylinder wasn't enough to lift the cylinder, they were asked to try one more time. Finally, 2 of the subjects were tested in the same setting, but during the AVF modality no auditory icon was presented to them. This forced the subject to detect and fix the errors just by listening to the sound sequence.

III. RESULTS

For the temporal performance, we recorded the time taken to complete each trial. Also, the time taken to fix an error, which was considered fixed when the subject moved the arm backwards and the robot hand returned to the last configuration before the error. The grasping performance was obtained by recording the average grip force in the Thumb and the Index finger. Also, we recorded for how long the EMG Grasp command was activated. The blinking rate was obtained from the EOG, the Heart rate in beats per minutes (bpm) was obtained from the ECG, the Skin Conductance Level (SCL) was obtained from the EDA. The results obtained were analyzed in SPSS 16.0 using the Non-Parametric Wilcoxon signed-rank test was used to measure the statistical effect between the AVF and VF modalities.

TABLE I. PERFORMANCE COMPARISON BETWEEN MODALITIES

Measurement	**Comparison**
Trial Duration	VF (43.67±1.7s) > AVF (37.52±0.89s) **
Trial Duration with an Error	VF (50.28±2.43s) > AVF (39.59±1.13s) **
Trial Duration without an Error	VF (37.29±1.71s) > AVF (35.25±1.31s)
Error Fixing Duration	VF (13.4±1.79s) > AVF (4.04±0.32s) **
Grip Force	VF (0.25±0.017V) > AVF (0.17±0.016V) **
EMG Activation	VF (3.13±0.17s) > AVF (2.4±0.12s) **

VF: Visual Feedback; AVF: Audiovisual Feedback*: $p < 0.05$; **: $p < 0.01$.

Table 1 shows a summary of the performance results obtained. As an overall the results showed better performance and a decrease in visual demand for the AVF modality. For example, Fig. 2 shows how long the subjects took to fix an error. Also, the applied grip force needed to lift the cylinder was significantly lower for the AVF modality. This result agrees with the result obtained for the EMG activation, where the subjects had to do less effort when using the AVF modality. Also, as can be observed in table 2, the results showed that the perceived mental effort is significantly lower ($p<0.05$) when using the AVF modality.

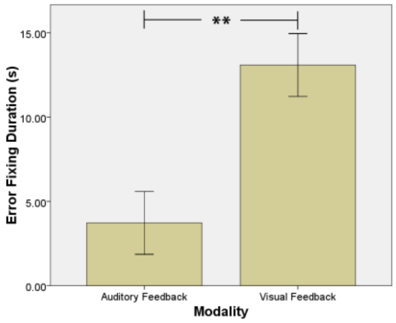

Fig. 2 Duration taken to fix an error after detection when an Auditory Icon was used in the Auditory Feedback Modality.

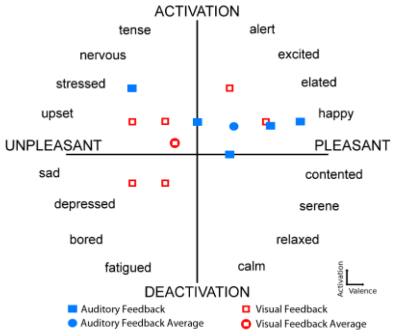

Fig. 3. Valence-Activation Map results based on the Self-Assessment Manikin.

As shown in Fig. 3, the subjects tend to feel more comfortable and pleasant when using the AVF modality ($p<0.05$). The blinking rate decreased considerably during the VF modality, which points out that there was a significantly more visual demand ($p<0.01$) when using the VF modality [13, 14]. When no auditory icon was used to enhance an error in the hand trajectory, we were expecting for the subjects to take similar time to detect and fix an error the VF and the AVF feedback. However, the subjects were able to detect and fix the errors faster in the AVF modality. Also, the duration of the whole trial was lower in this modality. Certainly, more subjects needs to be tested to obtain a robust result.

TABLE II. SELF-ASSESSMENT AND PSYCHOPHYSIOLOGICAL MEASUREMENTS COMPRAIONS BETWEEN MODALITIES.

Measurement	**Comparison**	**Description**
NASA TLX	VF (73.7±5.43%) > AVF (54±7.08%) *	Higher task difficulty with VF
Valence	VF (43.7±8.3%) < AVF (64.6±9.9%) *	More positive feeling with the AVF
Activation	VF (56.2±6.25%) < AVF (60.4±3.8%)	More arousal with AVF
Control	VF (41.7±11.02%)< AVF (62.5±11.18%)*	More confidence with AVF
Blinking Rate (blinks per sec)	VF (1.03±0.07) < AVF (1.7±0.08) *	Higher visual demand with VF
SCL	VF (1.13±0.016V) < AVF (1.15±0.014V)	More arousal with AVF
SCL during grasping	VF (1.14±0.021V) < AVF (1.23±0.017V)**	More arousal with AVF

VF: Visual Feedback; AVF: Audiovisual Feedback *: $p < 0.05$; **: $p < 0.01$. Results based on [13-15]

IV. DISCUSSION

As expected, the performance results presented in this study showed a better temporal performance in the AVF modality than in the VF modality for detecting and correcting an error in the robot hand's finger trajectories during the reaching phase. In this case the auditory cues are conveying faster and more accurately the information by enhancing visual perception, as described in [11]. During the reaching phase in the VF modality the subjects has to look at the hand at all times to successfully monitor the motions of the hand, which makes it more difficult to detect any errors in the trajectory of the fingers and reduces their blinking rate. Similar results can be found in [7-8], as they showed that subjects performed smoother motions in less time when auditory feedback was used for rehabilitation therapies.

Also, in this experiment the effect of using an auditory display to approximate the grasping force exerted in an object was shown. The results point out that the subjects have to do more physical effort than needed to realize the gripping task when only relying on visual input, since they keep the muscle force for longer time. On the other hand, the usage of auditory display doesn't give them an exact value of the force of the grip either, but at least they are able to intuitively relate the pitch of the sound to the force, which improves the overall performance. Richard P. et al. [12] showed similar results for force feedback when manipulating virtual deformable objects.

The NASA TLX and the psycho-physiological measurements were used to explore the subject's cognitive effort and by comparing the results obtained with the performance results we can see that they related to each other. The mental workload was considered higher when only the visual input was used to monitor the manipulation of the robot hand (VF modality) and it was found to have a low performance during the reaching phase and during the grasping phase. Therefore, as discussed in [13], we can narrow the interpretation of the results to a higher task difficulty when in the VF modality. This clarifies how the presentation of another congruent source of information improves the manipulation of a prosthetic hand. For this experiment, the heart rate didn't give any useful information. This might be due to the physical activity involved in the task, but as discussed in [15] a better data mining method could be used to explore the data.

Since the control scheme of the robotic hand used in this experiment was very similar to the myoelectric control scheme used by amputees, we wanted to measure to what the subjects were feeling when using the prosthetic hand. Therefore we used the self-assessment questionnaires and the psycho-physiological variables to explore arousal, valence and control of the subjects towards the system. As we hypothesized the results point out at the subjects becoming more confident and engaged in the task when the auditory display was used while improving their performance. This is an important finding since, during training, not only lowering the amputee's mental workload, but also improving their motivation is a requirement. Certainly, this should be further tested with actual amputees to explore how the results will translate. Also, the same setting has to be tested for longer period of time to explore long term training and fatigue factors. Also, different grasping patterns should be tested.

V. CONCLUSION

This experiment was designed to explore the effect of using an auditory display as a sensory feedback system for reaching and grasping movements for prosthetic applications. As hypothesized the results shows better performance, less attentional demand and mental workload, and an increase of the engagement factor when using the multimodal feedback. Not only the subjects were able to achieve the reaching and grasping task faster, but were able to approximate the grip force more accurately when auditory display was used, while reducing mental workload and improving their confidence.

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