AUDITORY DISPLAY AS AN AID FOR PROSTHETIC HAND MANIPULATION: PRELIMINARY RESULTS

Jose Gonzalez, Wenwei Yu

Chiba University
Medical Systems Department
Chiba-shi, Inage-ku, Yayoichou 1-33
jose.gonzalez@graduate.chiba-u.jp

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, sonification of the prosthetic hand's spatio-temporal and force information was implemented in a real setting. The main purpose is to explore the difficulties people face when using a prosthetic hand and how the usage of auditory information affects their performance. Preliminary results showed that the temporal performance and the grasping performance was improved, also that the mental effort was reduced, when using auditive feedback.

1. INTRODUCTION

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[1-2]. This lack of sensory feedback is a major drawback that many researchers are trying to cope by using indirect methods, such as electro-cutaneous or vibrotactile stimulation[3-6], to convey artificial tactile information from the artificial limb to the amputee.

These studies tried to help the amputee adapt the prosthesis to their body image by allowing more awareness when manipulating an object. Although the results obtained are very positive, they focus mainly on somatosensory information in order to improve object grasping. Therefore, during the reaching stage of the motion, the amputees still have to rely heavily on their vision due to the lack of spatio-temporal information feedback. Furthermore, one of the main drawbacks of these methods is the limited amount of information that can be transmitted and its high learning curve.

To improve the manipulation of a prosthetic device, kinematic information should be conveyed as proprioceptive feedback during reaching and grip pressure as somatosensory feedback[2]. This will allow better human-machine interaction during the whole reaching and grasping process.

Therefore, in order to enhance motor-sensory performance and awareness in prosthetic applications, auditory perception can be used as a redundant source of both kinematic and somatosensory information because of it's high dimensionality. Sonification offers multiple attributes, such as pitch, modulation, amplitude, spatial location, timbre, and brightness of a sound, which can be used to represent different variables or events of a movement[7]. Auditory feedback has been used for neuromotor rehabilitation therapies[8-12]. In human-computer interface it has played a major role for the analysis and understanding of multiple variables simultaneously [7, 13, 14].

Previous research in our laboratory showed how auditive feedback improved temporal performance when detecting spatio-temporal errors in a motion of a 2D computer simulated hand, but we wanted to go one step further and apply it into a real setting. The usage of real prosthetic hands adds many difficulties to the biofeedback system because of the unpredictability of the environment and the non-linearities of the device.

In order to measure the user's mental effort and feeling when interacting with a machine or robot, self assessment questionnaires are commonly used[15,16]. This questionnaires are very reliable, but in order to validate and corroborate the results psychophysiological measures can be used. For this study, the NASA TLX [16,17] self-assessment questionary is being used and the subject's EEG, ECG, skin impedance (EDA), and respiration are being measured. In the present paper only the NASA TLX scores will be discussed.

Therefore, our main purpose is to explore the difficulties people face when using a prosthetic hand and how the usage of auditory information affects their performance. For this study we focused on temporal and grasping performance when using a prosthetic hand in a static or fixed setting. Mental effort will be discussed briefly.

2. EXPERIMENT SETTINGS

2.1. Robot Hand

A tendon driven robotic hand was mounted on a tripod ready to grasp a bottle on a table, as shown in figure 1. This type of devices has the advantage that the shape of the grip can adapt to almost any object shape without needing to control many degrees of freedom. A Data Glove (5DT Ultra 5) was used to measure joint angles of the subject's hand to manipulate the prosthetic hand. Since this Data Glove has only 1 sensor per finger, the controllability of the hand was reduced to 1 degree of freedom in each finger. For this experiment, only the position of the robot hand's thumb, pointer, and middle finger was sampled (at 40Hz) in order to record and generate the sounds. We chose this setting to force the subject to concentrate on the robot hand's position instead of his hand since one position of

Figure 1. Tendon Driven Robotic Hand used in this study.

the robot hand can be achieved by different position of the subject's fingers.

2.2. Sonification

In a real prosthetic hand application the motion intention of the amputee has to be detected, triggering the robot hand to perform different movements in order to achieve the desired motion at different speeds. These movements are preprogram patterns that allows the robot hand to achieve different daily living motions and grasps (e.g. pinching, palm grasping). Therefore, if we only consider the grasping motion as a whole, we can reduce the amount of variables to feedback. In other words, instead of conveying the position of each finger of the robot hand individually, we can feedback only the position of a grasping type.

Sonification of individual fingers is possible, but it can become confusing for the user since they have to identify different sounds for each finger and their angles simultaneously, while monitoring if these sounds correspond to the motion they intended. This is why we chose to approach the problem by reducing the amount of variables as described before, this way the user can monitor the robot hand using different sounds for each type of grasping and modifying several sound attributes to identify the hand's position. For this study only the palmar grasping was used, in order to grasp a bottle (refer to figures 1 and 2).

The flexion of the fingers was divided in 8 different position, which were identify by different Piano major triads for the palmar grasp (refer to the audio files of each position: Position1.wav, Position2.wav, etc.). Position 1 was considered to be when all the fingers of the robot hand were extended, and position 8 when all the fingers were completely flexed. Since the task was to grasp a bottle, the robot hand never reached a completed flexed position (position 8), therefore only 5 position sounds were presented to the subjects. Additionally, in order to feedback other types of grasp, such as pinching, a sequence of a minor or any other type of triad can be used.

Since we are considering the hand motion as a whole, there should be a way to identify if one or more fingers are not following the fixed pattern of the grasp (e.g. due to a mechanical malfunction). For this purpose, to indicate an error in the trajectory, we used 3 different auditory icons for each

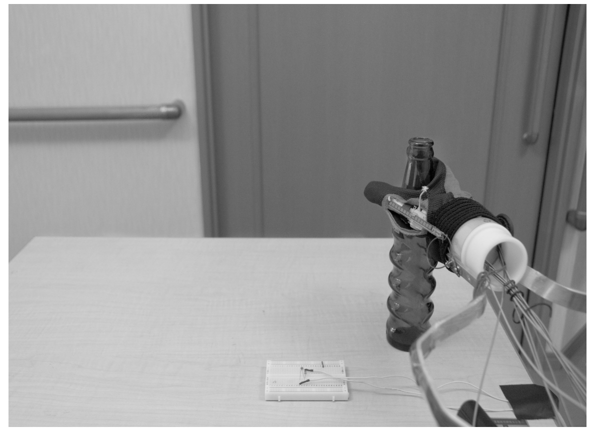

Figure 2. Subject's perspective of the setting used in this study.

finger: Thumb.wav, Pointer.wav, and Middle.wav. Finally, to indicate that the bottle was completely grasped an On/Off signal was presented as another auditory icon: Grasped.wav.

OpenAL API (Creative Labs) was used to playback the sounds. We chose to use OpenAL because it is very easy to perform 3D audio rendering, which we are planing on using for a dynamical setting of the current experiment in the near future.

2.3. Experiment Setting

6 male subjects between 22 and 30 years old, right handed, and with no sensory or motor impairment participated in this study, and were asked to come 2 consecutive days. The first day the experiment objective, tasks, and setting was explained. After, they completed a 30 minutes guided training of the feedback system. The second day each subject was tested in 3 different modalities: Auditory Feedback only control (AF), Visual Feedback only control (VF), and Audiovisual Feedback control (AVF). For each modality they had to perform 10 trials. At the end of each test, the subject had to answer the NASA TLX questionary.

The subjects were asked to wear the Data Glove and to sit beside the prosthetic device in a way that the device seemed to be part of their bodies. The subject's perspective of this setting is shown in figure 2. Since psychophysiological variables (EEG, ECG, EDA, Respiration) were being recorded during the tests, they were told to move as little as possible during the trials. Although the subject was able to manipulate all 5 fingers, they were told that only the Thumb, Pointer, and Middle finger were going to be tested.

The experiment's task consisted on closing the robot hand until the bottle was securely grasped, and then open it again until it was completely open. We made emphasis on the fact that they cannot rely on the position of their own hand, because the robot hand mechanism will not always yield the same position as their own hand. Errors in the motion of the Robot Hand's fingers were introduced randomly while closing or opening the hand during the trials. When an error was activated, one of the fingers stopped moving, therefore, the subject had to stop the motion, move the finger with the error backwards 1 position, and then continue with the motion. In this study, only 1 error per trial was presented.

Each trial started and finished when the Robot Hand's fingers were completely extended, but the subject had to fully grasp (exert enough force on the bottle so it would not slip if lifted) the bottle in order to finish the trial. A fully grasped bottle was indicated by an On/Off signal for the AF and AVF modalities. On the other hand, for the VF modality the subject had to approximate the grasp by what he was seeing. If the bottle wasn't completely grasped, then the subject had to close the robot hand again until fully grasp and then open it again.

2.3.1. Auditory Feedback only (AF)

For this feedback modality the subjects' eyes where covered, in order for them to monitor the Robot Hand's fingers position only by the sounds. To start a trial the subject was asked to leave their own hand completely opened, and wait for the sound of position 1 (Position1.wav) to be presented, then, start closing the hand until they heard the fully grasped sound (Grasped.wav), and then open the hand until they heard the sound of position 1 again. They had to repeat this for 10 times as a self-paced motion. If an error happened they had to move the affected finger backwards until they heard the previous position sound, and then continue with the motion.

2.3.2. Visual Feedback only (VF)

For the VF modality, the subject had to monitor the robot hand's motion only with their eyes. This is the same way current prosthetic hands have to be monitored and manipulated. A green LED was used to indicate when to start and finish each trial. The subject was asked to open his hand completely and wait for the LED to turn on, then start closing the robot hand until the bottle was fully grasped. In this case they had to approximate the grasping pressure, then, open the robot hand until the LED turned off. If the LED didn't turn off, then the bottle was not grasped completely, or the subject didn't detect and fixed an error, thus, had to close and open again until the LED turned off.

2.3.3. Audiovisual Feedback

In this modality the subject was able to monitor the robot hand using both the auditory and visual feedback as explained. During the training period only this modality was used in order to allow the subjects to get familiar with the system.

2.4. Data Evaluation

In this paper we are comparing the subject's temporal performance for 3 different modalities. We recorded the time taken to complete each trial and for each error to be fixed. An error was considered fixed when the subject moved the affected finger backward one position. This way we obtained how long it took for the subject to detect the error. We expected that, in the VF modality, the subjects were going to take more time to detect an error since it's more difficult to notice when a finger stops moving. Also, we expected the trials to last longer, for the VF modality, because it's difficult to approximate correctly a grasping force just by looking at the device, thus, the motion would have to be repeated to complete a trial.

Additionally, due to the lack of pressure sensors in the robot hand, a complete grasp was indicated by a digital signal. This is why in order to assess the grasping performance we measured how much the subjects flexed their own fingers in order to achieve a complete grasp. The output of the Data Glove was obtained as the percentage of finger flexure, where 0% indicated a totally extended finger and 100% totally flexed finger. For this application in order to achieve a complete grasp the subject had to close his hand around 60%. In the VF modality we expected the subjects to close their own hand more, than in the other 2 modalities since they have to approximate visually when the bottle was completely grasped.

We are also interested in exploring the subjects' mental workload when using a prosthetic device with and without an auditory aid. For this purpose we recorded several psychophysiological variables (EEG, ECG, EDA, Respiration) and asked the subjects to fill a self assessment questionnaire. For the present paper we are only going to refer to the results obtained with the self assessments questionnaires since the other variables need further analysis.

The NASA TLX [9] was used to measure the subjective mental workload of the system. The overall workload score obtained is based on a weighted average rating of 6 sub scales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration. This scale has been successfully used to assess workload in different human-machine interfaces applications[16]. In order to calculate the overall score each sub scale has to be weighted by presenting a pair of factors and asking the subject to choose what he thinks contributed more to the workload of the task (there are 15 pair-wise comparisons). The final weights are obtained by summing the times each factor was selected. This weights range from 0 (no important) to 5 (more important than any other factors). After, the subjects have to rate each of the factors in a scale divided in 20 equal intervals anchored by a bipolar descriptors (e.g. High/Low). Finally, each rating was multiplied by the weight given to that factor and all the results were summed and divided by 15.

3. Results

An Analysis Of Variance (ANOVA) was used to explore and compare the data obtained using SPSS 16.0. Figure 3 shows the time it took for the subjects to complete a trial. A significant difference between subjects ($P<0.05$)was found. Also, a Tukey HSD and Bonferroni Post Hoc tests showed no significant difference between modalities AF and AVF ($P=0.884$ and $P=1.0$), but a significant difference between modalities AF and VF ($P=0.002$) and modalities AVF and VF ($P=0.008$ and $P=0.009$). These results support our hypothesis, where the VF modality takes more time than the AF and AVF modalities to complete a trial, but there is a large variability between subjects.

We applied the same tests to the error correction timing data. In this case, a comparison between subjects didn't show any significant difference ($P=0.4$), and the post hoc test showed that there is no significant difference between the AF and AVF ($P=0.896$ and $P=1.0$), but there was a significant difference between the modalities AF and the VF ($P<0.001$) and between the AVF and VF ($P<0.001$). Again, this results were as expected because during the VF modality it is more difficult to detect the

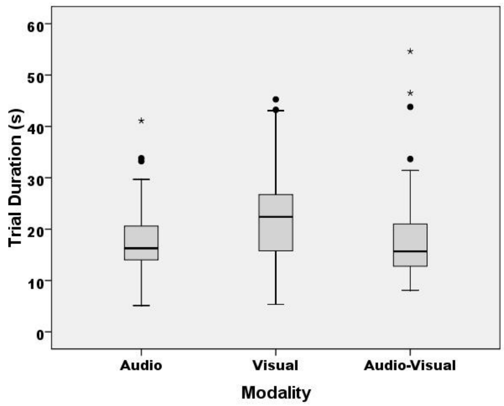

Figure 3. Duration of a trial in seconds for each modality

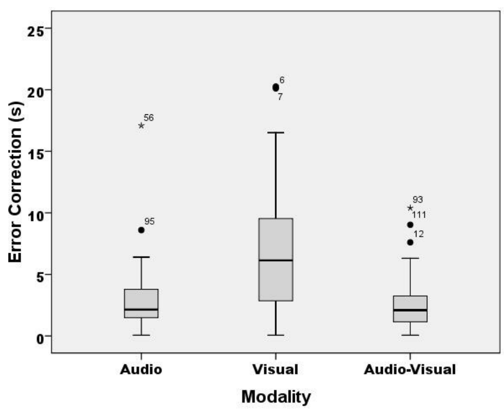

Figure 4. Time in seconds to detect and correct an error

error fast, specially for the pointer and middle finger that were semi-blocked by the bottle. What it's interesting, and needs further tests and analysis, is that despite the large variability in the trial duration, there wasn't a statistical variability when fixing the error. The results are shown in figure 4.

The subject's hand final position when grasping is shown in figure 5. A statistical difference was found between subjects ($p<0.01$) and between modalities($p<0.01$). The Post Hoc tests showed that there was no significant difference between AF and the AVF modalities ($P=0.287$), but a significant difference between AF and VF ($P<0.001$) was found. For the modalities AVF and VF a statistical difference ($P<0.001$) was also found. This results were also as expected, since during the VF modality the subjects have to rely on what they see as a complete grasp. Also, a large variability between subjects can be observed in the AF and the AVF modalities which requires further experimentation.

Finally, figure 6 shows the results for the Nasa TLX self assessment test. We can observe that VF modality has the highest workload, and the AVF has the lowest work load when manipulating the prosthetic device. This results agrees with the notion of a high consciousness burden for the user when relying only on vision when using a prosthetic device, and shows how the usage of auditive feedback reduced the mental effort. This results still have to be validated and corroborated with the psychophysiological data obtained in the experiment, and more subjects need to be tested in order to have reliable results.

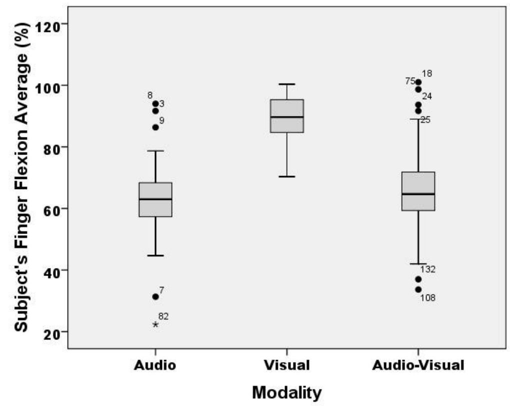

Figure 5. Grasping final position for each modality.

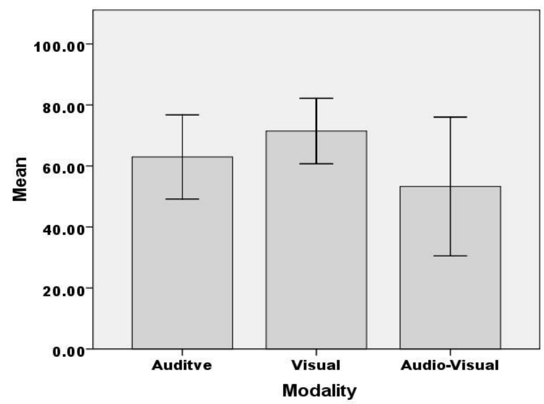

Figure 6. Average of total mental workload for each modality.

4. Discussion

P.Herberts *et al.* argued, in [1], that sensory feedback should not be intended to replace directly normal hand sensation, but to be used as an aid for manipulating the prosthesis, in a way to compare the performance of the robotic limb with the intended motion. Following this thought, the auditory information used in this study was aimed as a redundant source of information that can be couple with different feedback modalities in the future, such as electro-cutaneous stimulation. This way the auditive feedback system can be used as a tool to aid in learning not only the control of the prosthetic hand, but also of other feedback schemes.

The preliminary results presented in this paper show better temporal performance in the AF and AVF modalities than in the VF modality. We can argue that the reason for this result is the fact that the subject is interacting more directly with the prosthetic device because auditory cues convey faster and more accurately the relative position and the moment an error occurred, than when the subject is only looking at the hand. Similar results were showed by H. Huang et al., where subjects performed smoother motions in less time when auditory feedback was presented[10]. We were expecting this results since it takes some time to detect that a finger has stopped moving, specially the pointer and middle finger that were partially blocked by the bottle (figure 2).

Also, since the subject had to approximate the grasping force of the bottle in the VF modality, we were expecting that in some trials the subject wasn't going grasp completely the object, thus, having to close and open the hand again. This situation happened approximately once per subject because most of the subjects opted on closing more their own hands, which can be seen from the grasping finger flexion results presented on figure 3. This results basically show the low ability to approximate correctly the grasping force that its needed to be applied to an object, therefore the user will end up doing more mental and physical effort. Richard P. et al. showed similar results for force feedback when manipulating virtual deformable objects[18]. To make this comparison more realistic Force sensors will be added to the robotic hand in order to investigate this situation directly. This way the subject will have to approximate the grasping force as well, but using sounds.

The mental effort results show that VF modality is more cognitive demanding than the others. In this case we were expecting the AF modality to be very similar to the VF modality, since the subject only had a short training period to learn the different sounds, and having the eyes covered may increase the mental workload. It can be difficult for the subjects to relate the sounds to the physical variables without proper training, leading to confusion, but this doesn't seem to be the case for this experiment. The subjects reported that sometimes they had trouble distinguishing the error sound of each finger, but as an overall it was very intuitive. More subjects have to be tested, and include the analysis of the psychophysiological measurements in order to verify this results.

The sonification implemented in this study is not optimal. As discussed by Hermann, T. in [14] a model-based approach for sonifying the position might be more suitable for this kind of application, since the system is highly non-linear and the discrete events used limits the spatial resolution. Also, it is prone to display multiple fast sounds when the finger's angle is in the limit between 2 positions, making the feedback confusing. On the other hand, the use of auditory icons to mark the errors on each finger is very intuitive for the subjects and easy to learn. Another factor affecting the system performance is the low sampling rate used for the robot hand sensors. This problems are currently being fixed.

5. Conclusion

The preliminary results presented in this paper show better temporal performance of the auditive and audiovisual feedback modalities, than the visual feedback modality. Also, they point out the difficulty to approximate accurately the force needed to grasp an object relying only on only visual information. Finally, the results indicate the high mental effort a person has to make when manipulating a prosthetic device relying only on their vision, and how this effort seems to be reduced when auditive feedback is added to the human-machine interaction.

Currently more subjects are being tested in order to obtain more reliable results. Also, a dynamic version of this setting, where the subject uses the prosthetic device to reach and grasp and object, is being designed.

6. REFERENCES

[1] Childress, D. (1980), *Closed-loop control in prosthetic systems: Historical perspective*, Annals of Biomedical Engineering Vol.8, No.4-6, pp. 293-303.

[2] Herberts, P, Körner, L (1979). *Ideas on sensory feedback in hand prostheses*. Prosthet Orthot Int, Vol.3, No.3,pp.157-62

[3] Stepp, C. & Matsuoka, Y. (2010), *Relative to direct haptic feedback, remote vibrotactile feedback improves but slows object manipulation.* EMBC 2010, IEEE, pp.2089 -2092.

[4] A. Hernández, *et al.* (2005) *FES as Biofeedback for an EMG Controlled Prosthetic Hand.*TENCON 2005, IEEE, pp.1 - 6

[5] G.S.Dillon, *et al.* (2004) *Residual Function in Pheripheral Nerve Stumps of Amputees.* The Journal of Hand Surgery, Vol.29, No.4, pp. 605-615

[6] A.Y.J. Szeto and F. A. Saunders. (1982) *Electrocutaneous Stimulation for Sensory Communication in Rehabilitation Engineering.* Biomedical Engineering, IEEE, Vol.29, No.4, pp.300-308

[7] Effenberg, A. (2005) *Movement sonification: Effects on perception and action*, Multimedia*, IEEE* 12(2), pp.53 - 59.

[8] S.Kousidou, N.G. *et al.*(2007) *Task-orientated biofeedback system for the rehabilitation of the upper Limb.* IEEE Conference on Rehab. Robotics, pp. 376

[9] C.Ghez, *et al.* (2000) *An Auditory Display System for Aiding Interjoint Coordination*, ICAD'2000

[10] H.Huang, *et al.* (2006) *Recent developments in biofeedback for neuromotor rehabilitation*, Journal of NeuroEng. and Rehab. Vol. 3, No. 11

[11] Vogt, K. *et al.*(2010), *PhysioSonic - Evaluated Movement Sonification as Auditory Feedback in Physiotherapy.* In Sølvi Ystad *et al.* ed., 'Auditory Display', Springer Berlin / Heidelberg, pp. 103-120.

[12] Dozza M. *et al.* (2004) *A portable audio-biofeedback system to improve postural control.* EMBS, IEEE, Vol. 7, No. 4, pp.779-802

[13] Effenberg, A. *et al.* (2005), *MotionLab sonify: a framework for the sonification of human motion data.* Information Visualization 2005, IEEE, pp. 17 - 23.

[14] Hermann, T. & Hunt, A. (2005) 'Guest Editors' *Introduction: An Introduction to Interactive Sonification*, *IEEE Multimedia* Vol. 12, pp. 20-24.

[15] Bethel, C. *et al.*(2007) *Survey of Psychophysiology Measurements Applied to Human-Robot Interaction.* Robot and Human interactive Communication, IEEE, pp.732-737.

[16] Fairclough, S.H. & Ewing, K. (2010) *The effect of an extrinsic incentive on psychophysiological measures of mental effort and motivational disposition when task demand is varied.* Human Factors and Ergonomics Society, pp. 259-263

[17] Hart, S. G. (2006). *NASA-Task Load Index (NASA-TLX); 20 Years Later*. Human Factors and Ergonomics Society, pp.904-908.

[18] Richard P. *et al.* (1994) *A Comparison of Haptic, Visual and Auditive Force Feedback for Deformable Virtual Objects.* ICAT'94, pp. 49-62