34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Grasping Force and Slip Feedback through Vibrotactile Stimulation to be Used in Myoelectric Forearm Prostheses

Heidi J.B. Witteveen, Johan S. Rietman, and Peter H. Veltink, *Member, IEEE*

Abstract— **User feedback about grasping force or slip of objects is lacking in current myoelectric forearm prostheses, resulting in a high number of prosthesis abandonment, because a high level of concentration is required to hold an object. Several approaches to provide force feedback to the user via vibrotactile stimulation have been described in literature, but none of them have investigated the optimal stimulation parameters. This study describes an evaluation of three modulation techniques to provide force feedback. Furthermore, the same modulation techniques to provide slip feedback were evaluated, which has not been described before. The performance in virtual object holding tasks was significantly improved in most cases compared to the non-feedback situation, but at the cost of an increased task duration.**

I. Introduction

Current myoelectric forearm prostheses offer an increasing level of functionality. However, the number of forearm prostheses being used on a daily basis remains low. One of the reasons of this prosthesis abandonment is the lack of user feedback about grasping force or occurring slip [1]. In situations without sensory feedback about grasping force, people tend to apply too much force to avoid slippage of objects [2], requiring more muscle activity than necessary. Furthermore, difficulties in handling of delicate objects will be experienced when no grasping force feedback is present. Early approaches to provide grasping force feedback to prosthesis users mainly focused on electrotactile stimulation [3,4,5] providing force feedback through amplitude, pulse frequency or pulse width modulation respectively. Because the range between sensation and pain thresholds for electrotactile stimulation is rather small and due to recent miniaturization of vibrotactile stimulators, latest studies focus more on vibrotactile stimulation [6-11]. In most studies, a single stimulator (C2 tactor) is used and force is translated through frequency [6], pulse frequency [8,10] or amplitude modulation [9, 10]. In two other studies, small coin motors were used to provide force feedback through frequency modulation [7,11]. The use of an array of these coin motors also shows some possibilities, but has only been used in one study on force feedback [12]. The outcomes of these studies are highly variable, ranging from no improvements compared to the non-feedback situations [8] to a measured reduction in muscle force needed to lift objects [11]. These variability is probably caused by the lack of a thorough evaluation of the possible stimulation methods that can be used. Only in one study a comparison is made between pulse frequency and amplitude modulation [13], but not in relation to an array of coin motors. In this study we have evaluated the performance of healthy subjects in a virtual object holding task, while force feedback was provided through vibrotactile stimulation. Amplitude and pulse frequency modulation via a C2 tactor and position modulation through an array of coin motors were used to provide the vibrotactile stimulation. Furthermore, we also evaluated these modulation techniques for feedback about slip of objects. Potentially, slip feedback can be more useful than grasping force feedback, because no preliminary information about the weight or surface of an object is needed.

II. Methods

A. Subjects

Measurements were performed on 15 healthy subjects (26.4 ± 2.4 years; 6 m, 9 f), all students and staff of our department. All subjects did not have any experience with vibrotactile stimulation before and did not have any sensory or skin problems of their forearm. All were right-handed or at least control the computer mouse with their right hand. Subjects were informed about the study via an information letter and all signed informed consent before the start of the experiment. The study protocol has been approved by the local medical ethical committee (Medisch Ethische ToetsingsCommissie Twente).

B. Materials

Vibrotactile stimulation was applied either through an array of 8 commercially available coin motors (Ineed, China) or a single C2 tactor (Engineering Acoustics, Inc., Casselberry, Florida, USA). These coin motors were chosen, because they already showed good results [11], are easy to use, small and low-priced. A rotating inner mass results in stimulation in a tangential direction to the skin. All 8 stimulators were activated with a driving current of 44 mA, which was adjusted if necessary to create equally perceived amplitudes. The coin motors were driven by a custom build control unit and a National Instruments DAQ system (NI USB-6211), controlled by a Labview syntax. The C2 tactor has already been used in a wide range of military and

This work is supported by the Ministry of Economic Affairs (Pieken in de Delta), Overijssel, the Netherlands, grant PID082035/1.6.1b

H.J.B. Witteveen is with the Biomedical Signals and Systems department, MIRA institute, University of Twente, 7500 AE Enschede, The Netherlands (phone: +31 (0)53 489 2766, fax: +31 (0)53 489 2287, e-mail: h.j.b.witteveen@utwente.nl).

J.S. Rietman is with the Roessingh Research and Development, 7500 AH Enschede, The Netherlands, and with the Biomechanical Engineering department, MIRA institute, University of Twente, 7500 AE Enschede, The Netherlands.

P.H. Veltink is with the Biomedical Signals and Systems department, MIRA institute, University of Twente, 7500 AE Enschede, The Netherlands

biomedical applications. Stimulation is applied in a vertical direction to the skin. The stimulation frequency was set to 250 Hz, because this is the resonance frequency of the C2 tactor and important mechanoreceptors in the skin, Pacinian corpuscles, are most sensitive to this frequency. The amplitude and pulse frequency of stimulation were controlled by another NI DAQ system and a Labview syntax. All stimulators were attached to the skin by double-sided adhesive rings (EEG Kleberinge, The Netherlands).

C. Experimental setup

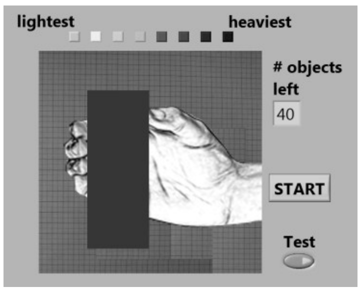

Figure 1. Virtual setup comprising a hand holding an object, which weight is color-coded.

To block the available sensory pathways of the healthy subjects, a virtual representation of a hand holding a cylindrical object was built in Labview (Labview Inc., 2009b, USA). The grasping force applied to the object was controlled by the subjects through the scroll wheel of a computer mouse. The 'clicks' from this mouse wheel were removed and a random varying gain between the level of scrolling and the grasping force was introduced to force the users to fully rely on grasping force feedback through the vibrotactile stimulation.

The weight of the displayed object is randomly varied and presented to the subjects via a color bar (see Fig. 1). 8 different weights, corresponding to 8 feedback levels were used and the applied force is also classified to 8 discrete force levels. During the first two seconds of the training phase a thin horizontal bar supported the object. After these two seconds, the supporting bar was removed and the result of the applied force was displayed. When the applied force was not correct, the object was either dropped or squeezed and the same object was shown again with a maximum of 5 trials per object. In the experimental phase, the subject was asked to apply the presumed necessary force level as fast and accurate as possible, but the effect was not shown and after 4 seconds the next object was presented. The number of objects to be held in the training phase was 20 and 40 in the experimental phase.

D. Feedback

Either feedback about the grasping force or slip was given. Level of slip in this study is defined as the level of movement of the object in relation to the hand, discretized in 8 levels. For grasping force feedback, the applied force was directly fed back to the subjects. Based on the visual weight information, the suitable grasping force must be determined. For slip feedback the task was to minimize the slip, by increasing the grasping force. During slip feedback, the visual representation of the weight of the object should not be necessary in the grasping tasks and is therefore blocked in half of the cases, by showing only white objects for every weight.

E. Stimulation

Three methods of stimulus modulation were used: (1) position (coin motors), (2) pulse frequency and (3) amplitude (C2 tactor) modulation. An array of 8 coin motors, placed around the thickest part of the forearm, was used to provide position modulation. Each force / slip level corresponded to activation of one of the coin motors. For amplitude and pulse frequency modulation an increase in force level or slip corresponded to a linear increase in amplitude or pulse frequency. The amplitude was varied between 1 and 4.5 Volts (0.5 V increase per force level) and pulse frequency between 4.35 and 50 Hz, which corresponded to stimulus intervals of 230 to 20 msec. at a 50% duty cycle. The C2 tactor was placed at the dorsal side of the forearm, halfway between the elbow and wrist.

F. Experimental conditions

Both grasping force and slip feedback were provided for all three stimulation modulation methods. For all feedback options, a training session was applied before the measurement session. A control measurement (no vibrotactile and visual feedback), was performed between the change of stimulators and at the end of the experiment. No training was provided in the non-feedback situation, but the whole experimental setup was the same. For slip feedback, an extra measurement was performed without the visual weight information. The order of experimental conditions was randomized to avoid training effects.

G. Outcome parameters and statistical analysis

For the training phase, the number of attempts needed to reach the correct force level was determined and averaged over all objects. For the experimental phase, the applied force (discrete level) was compared to the required grasping force and based on this, the percentage correct force levels and the mean absolute deviation from the correct force level were determined. The task duration was calculated as the time needed to reach the final force level and summed over all 40 objects. ANOVA analyses and additional t-tests were performed to statistically evaluate the difference between stimulation parameters (p=0.05).

III. RESULTS

A. Descriptive statistics

The mean absolute error between the defined and real grasping force level ranged between 0.3 and 0.61 for every combination of feedback and modulation method compared to 1.22 for non-feedback. The mean percentages correct force levels ranged from 54.2 to 75.7 % compared to 32.8 to 65.6 % for the non-feedback situations, which is higher than expected for pure guessing. The mean duration of the tasks was between 62.9 and 73.2 s and 50.7 s during non-feedback. The combination of slip feedback and pulse frequency modulation was left out from this evaluation, because this showed extreme deviations from the other values.

B. Visual feedback

Visual feedback about the weight of the objects was blocked in half of the cases of the slip feedback experiments. The effect on performance was evaluated via a paired-samples t-test for every modulation technique and every outcome parameter. No significant differences (p-values ranging from 0.076 to 0.959) were found. Therefore, the outcome parameters of slip feedback were averaged over both visual feedback conditions and used in further analysis.

C. Feedback method

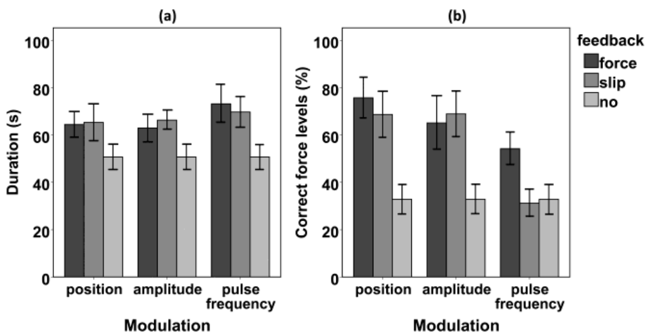

Figure 2. Mean and 95% c.i.'s of (a) the duration of the tasks and (b) the percentage correct force levels for each modulation method (1method for the coin motors and 2 methods for the C2 tactor) and feedback method.

A clear interaction effect ($p<0.001$) between the type of feedback and the used modulation was found via ANOVA analysis of all parameters. Therefore, separate ANOVA analyses were performed for all modulation techniques.

Through the use of an array of coin motors (position modulation) the performance in the object holding task is significantly improved (see Fig. 2b) compared to the non-feedback situations (all p-values <0.001). However, the time needed to perform the tasks was also significantly increased (see Fig. 2a) for both feedback methods in comparison to the non-feedback situation (p=0.002 and <0.001 respectively). all performance measures were equal for force and slip feedback. The number of attempts needed in the training phase was comparable for both feedback methods (p=0.1).

Also for amplitude modulation the performance parameters were significantly higher for both feedback methods compared to no feedback ($p<0.001$) and showed no differences between force and slip feedback.

Via pulse frequency modulation, slip feedback did not increase the performance in the experimental tasks compared to the non-feedback situation (p-values from 0.67 to 1). However, force feedback through pulse frequency modulation did increase all performance measures. The number of attempts needed to successfully perform the tasks was also significantly higher for slip feedback compared to force feedback (p=0.004). Furthermore, also in these cases the duration of the tasks was significantly higher than in the non-feedback situation.

D. Stimulation modulation

Due to the interaction effect between the type of feedback and the used modulation, separate ANOVA analyses were performed for both feedback methods.

In case of force feedback, no differences were found between the three modulation techniques for all three performance measures (p-values ranging from 0.05 to 0.80), except for the number of attempts in the training phase, which was significantly lower (p=0.001) for the position modulation in comparison to pulse frequency modulation (see Fig. 3). Furthermore, the duration of the tasks was significantly higher when pulse frequency modulation was used (p=0.01 and 0.03) compared to the other two modulation techniques.

In case of slip feedback, the performance parameters were highly comparable for position and amplitude modulation (all p-values were 1), while pulse frequency modulation showed significantly lower performances and a higher number of attempts in the training phase compared to the other modulation techniques ($p<0.001$). No differences in duration were found between all three modulation techniques ($p>0.5$).

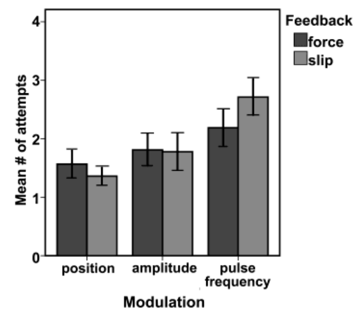

Figure 3. Mean and 95% c.i.'s of the number of attempts used in the training phase for each modulation technique and feedback method.

IV. DISCUSSION

A. Feedback method

Although the performance without feedback was higher than expected, likely caused by the known endpoints of the force range, it is shown that the addition of artificial force feedback improves the performance, expressed in a significant decrease in absolute error and increase in percentage correct force, in a virtual object holding task. This improvement is not seen in each study on force feedback. Chatterjee et al [8] used a C2 tactor to provide force feedback via pulse width and pulse frequency modulation, but found no improvement in distinguishing 3 force levels compared to the non-feedback situation. We also experienced some problems with pulse frequency modulation, but only for the slip feedback situation, while the performance in force feedback with 8 levels was significantly better compared to the non-feedback situation. Pylatiuk et al. used a single coin motor to provide force feedback and they did show a reduction in applied forces by prosthesis users [11]. However, in another study, force feedback via frequency modulation of one coin motor was not shown to be successful [6]. They have improved this by the use of three coin motors on top of each other [10]. In our study we proposed the use of an array of coin motors to provide more feedback levels which shows to be successful. An improved performance together with an increased duration of the tasks was seen in the study of Stepp et al. [9], who used force feedback through amplitude modulation of a C2 tactor. This increase in duration of the tasks is also seen in our study. However, it is expected that the duration can be drastically reduced after periods of training with the feedback, which must be tested in future experiments.

Slip feedback to the user has not been described before. It has been incorporated already in several commercially available prostheses, but always to automatically control the grasping of the prosthesis. The advantage of the use of slip feedback instead of grasping force feedback is that there is no need for preliminary information about the weight or roughness of the object. Our results have shown that this visual weight information indeed is not necessary, because performance was not decreased when blocking the weight information on the screen. Furthermore, we showed no difference in performance compared to the force feedback method. These results are promising, but it should be further investigated, whether the slip can be detected and translated in different feedback levels, if it is possible to give feedback before the definite slip of the objects and if it is fast to react and change the grasping force.

B. Stimulation modulation

We have shown that better performances can be reached with position and amplitude modulation, especially for slip feedback. The performance with slip feedback through pulse frequency modulation was surprisingly low, which is likely caused by the hardly distinguishable lowest pulse frequency levels. A non-linear relation between slip and pulse frequency, with larger intervals between the lowest frequencies, can probably solve this issue. Problems with pulse frequency modulation were also seen by Chatterjee and Stepp *et al.*, who, however, used other pulse frequency levels [8,13]. Amplitude modulation seems to be the most intuitive feedback method, because the number of attempts necessary in the training phase is lowest, especially for slip feedback where it performs significantly better than both other modulations. Furthermore, it seems more intuitive to provide force feedback through a single stimulator, because this is more related to the actual sense of force. Amplitude modulation would be the best option to provide force feedback, especially in combination with position feedback through position modulation.

C. Methodological considerations

We have used a virtual environment, consisting of a hand holding objects with different weights, instead of a real hand to block the normal sensory pathways of healthy subjects. Healthy subjects were chosen, because the number of amputee patients is rather small and this study was meant to be a first preliminary study to evaluate the stimulation parameters to provide slip or force feedback. Our findings, however, should be validated on prosthesis' users.

V. Conclusion

It is shown that an array of coin motors as well as an amplitude modulated C2 tactor can successfully provide both force and slip feedback in a virtual grasping task. These results will be extended to real life grasping and evaluation on end users.

Acknowledgment

The authors would like to thank Ed Droog for the development and realization of the measurement setup.

References

[1] D. J. Atkins, D. C. Y. Heard, and W.H. Donovan, "Epidemiologic overview of individuals with upper-limb loss and their reported research priorities", *Journal of Prosthetics and Orthotics,* 1996, vol. 8, pp. 2-11.

[2] G. Westling and R. S. Johansson, "Factors influencing the force control during precision grip", *Experimental Brain Research,*1984, vol. 53. pp. 277-284.

[3] T. W. Beeker, J. During, and A. Denherto, "Artificial touch in a hand-prosthesis", *Medical & Biological Engineering*, 1967, vol. 5, pp. 47-49.

[4] R. N. Scott, R. H. Brittain, R. R. Caldwell, A. B. Cameron, and V. A. Dunfield, "Sensory-feedback system compatible with myoelectric control", *Medical & Biological Engineering & Computing,* 1980, vol. 18, pp. 65-69.

[5] R. E. Prior, J. Lyman, P. A. Case, and C. M. Scott, "Supplemental sensory feedback for the va/nu myoelectric hand. Background and preliminary designs", *Bull Prosthet Res,* 1976, pp. 170-91.

[6] C. Cipriani, F. Zaccone, S. Micera, and M. C. Carrozza, "On the shared control of an emg-controlled prosthetic hand: Analysis of user-prosthesis interaction", *IEEE Transactions on Robotics,* 2008, vol. 24, pp. 170-184.

[7] J. L. Pons, R. Ceres, E. Rocon, D. Reynaerts, B. Saro*, et al.* "Objectives and technological approach to the development of the multifunctional manus upper limb prosthesis", *Robotica*, 2005, vol. 23, pp. 301-310.

[8] A. Chatterjee, P. Chaubey, J. Martin, and N. Thakor, "Testing a prosthetic haptic feedback simulator with an interactive force matching task", *Journal of Prosthetics and Orthotics,* 2008, vol. 20, pp. 27-34.

[9] C. E. Stepp and Y. Matsuoka, "Relative to direct haptic feedback, remote vibrotactile feedback improves but slows object manipulation", in *Proceedings of the 'Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE'*, 2010, pp. 2089-2092.

[10] C. Cipriani, M. D'Alonzo, and M. C. Carrozza, "A miniature vibrotactile sensory substitution device for multi-fingered hand prosthetics", *IEEE Transactions on Biomedical Engineering,* 2011, vol. 59, pp. 400-408.

[11] C. Pylatiuk, A. Kargov, and S. Schulz, "Design and evaluation of a low-cost force feedback system for myoelectric prosthetic hands", *Journal of Prosthetics and Orthotics,* 2006, vol. 18, pp. 57-61.

[12] I. Saunders and S. Vijayakumar, "The role of feed-forward and feedback processes for closed-loop prosthesis control", *Journal of Neuroengineering and Rehabilitation*, 2011, vol. 8.

[13] C. E. Stepp and Y. Matsuoka, "Vibrotactile sensory substitution for object manipulation: Amplitude versus pulse train frequency modulation", *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 2012, vol. 20, pp. 31-37.