Vibro- and Electrotactile User Feedback on Hand Opening for Myoelectric Forearm Prostheses

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

***Abstract*—Many of the currently available myoelectric forearm prostheses stay unused because of the lack of sensory feedback. Vibrotactile and electrotactile stimulation have high potential to provide this feedback. In this study, performance of a grasping task is investigated for different hand opening feedback conditions on 15 healthy subjects and validated on three patients. The opening of a virtual hand was controlled by a scroll wheel. Feedback about hand opening was given via an array of eight vibrotactile or electrotactile stimulators placed on the forearm, relating to eight hand opening positions. A longitudinal and transversal orientation of the array and four feedback conditions were investigated: no feedback, visual feedback, feedback through vibrotactile or electrotactile stimulation, and addition of an extra stimulator for touch feedback. No influence of array orientation was shown for all outcome parameters (duration of the task, the percentage of correct hand openings, the mean position error, and the percentage deviations up to one position). Vibrotactile stimulation enhances the performance compared to the nonfeedback conditions. The addition of touch feedback further increases the performance, but at the cost of an increased duration. The same effects were found for the patient group, but the task duration was around 25% larger.**

***Index Terms*—Electrotactile stimulation, hand opening feedback, myoelectric forearm prostheses, vibrotactile stimulation.**

I. INTRODUCTION

DESPITE the large improvements made in the development of myoelectric upper-limb prostheses, the number of prostheses that is not used on a regular basis remains quite high (30–60%) [1], [2]. Several surveys have indicated that prostheses' abandonment is related to the poor functionality of the currently available prostheses and the lack of sensory feedback [1], [3], [4]. In a recent study, in which representative prosthesis users were involved, it has been shown that feedback about the gripping force and the hand opening are the most important aspects to be incorporated in future myoelectric forearm prostheses [5]. Feedback about the opening of the hand is especially important in situations where no visual feedback is available. Furthermore, a prosthesis that comprises hand opening feedback may reduce the amount of visual attention needed to control the prosthesis and thereby increase the acceptability of the prosthesis by the user. Several approaches to provide hand opening feedback for upper-limb prostheses have been described. The use of phantom sensations to provide hand opening feedback was investigated at an early date [6]. For this approach, two vibrotactile stimulators, activated with different amplitudes to create (phantom) sensations in between the stimulators, were used to provide information about the elbow angle of an upper-limb prosthesis. A direct connection to the afferent nerves was investigated by Dhillon and Horch who used implanted electrodes to provide information about the elbow range [7]. Electrostimulation of the skin was evaluated by Prior and Lyman to provide feedback about the hand opening [8]. A single electrode provided feedback by pulse rate modulation, which resulted in an increased ability to distinguish object sizes. Another way of providing feedback about the hand opening has been published more recently [9], [10]. The hand opening of a virtual hand was fed back to the subjects by moving the real index finger via a motor, which in this way provided proprioceptive motion feedback.

Despite these developments and the distinct need for hand opening feedback, no myoelectric forearm prostheses are available today that provide any sensory feedback about the opening of the hand to the user. One of the reasons probably is the lack of proper investigation of the optimal parameters to provide the hand opening feedback. Intuitively, the direct stimulation of the individual nerves will provide the best solution to close the loop of the control of a myoelectric prosthesis, but is also the most difficult method to successfully implement in a prosthesis, due to the selectivity of the sensory system. On the other hand, vibrotactile and electrotactile stimulations seem to be of high potential to provide feedback in myoelectric prostheses, because they are easy to apply, nondisturbing to the environment and noninvasive, as already stated by Kaczmarek *et al*. [11]. However, no studies have been conducted on the objective comparison of these stimulation methods to provide hand opening feedback.

Providing position feedback through an array of stimulators, in which each stimulator corresponds to a position, might be a method with higher ecological validity than methods using amplitude or frequency modulation, to provide hand opening feedback. The phantom sensation approach of Mann and Riemers [6] can be seen as an early application of such an approach. Another

Manuscript received November 16, 2011; revised March 30, 2012; accepted April 28, 2012. Date of publication May 22, 2012; date of current version July 18, 2012. This work was supported by the Ministry of Economic Affairs (Pieken in de Delta), Overijssel, The Netherlands, under Grant PID082035/1.6.1b. *Asterisk indicates corresponding author*.

*H. J. B. Witteveen is with the Department of Biomedical Signals and Systems MIRA, Institute for Biomedical Technology and Technical Medicine, University of Twente, 7500 AE Enschede, The Netherlands (e-mail: h.j.b.witteveen@utwente.nl).

E. A. Droog and P. H. Veltink are with the Department of Biomedical Signals and Systems MIRA, Institute for Biomedical Technology and Technical Medicine, University of Twente, 7500 AE Enschede, The Netherlands (e-mail: e.droog@utwente.nl; p.h.veltink@utwente.nl).

J. S. Rietman is with the Roessingh Research and Development, 7500 AH Enschede, The Netherlands, and also with the Department of Biomechanical Engineering MIRA, Institute for Biomedical Technology and Technical Medicine, University of Twente, 7500 AE Enschede, The Netherlands (e-mail: j.s.rietman@rrd.nl).

Digital Object Identifier 10.1109/TBME.2012.2200678

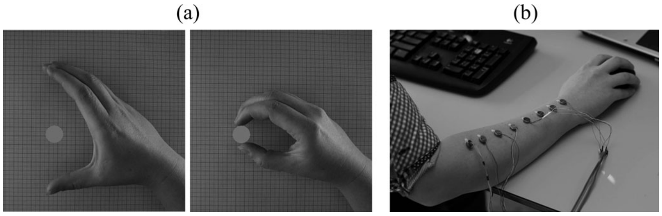

Fig. 1. Experimental setup. (a) Virtual representation of the moving hand and one of the objects to be grasped. (b) Vibrotactile feedback array placed in the longitudinal orientation.

application of an array of stimulators is shown by Antfolk *et al.*, who used five servomotors, placed on the arm, to provide information about the different fingers to be touched [12].

In this study, the use of an array of eight stimulators to provide hand opening feedback is investigated, whereby the methods of electrotactile and vibrotactile stimulations are compared objectively on healthy subjects and validated on a small patient group.

II. METHODS

A. Subjects

Measurements were performed on 15 healthy subjects (age, 24.6 ± 2.9 yrs.) and three patients (age, 45.5 ± 9.2 yrs., one forearm amputee, two congenital). The mean stump length of the patients was 13 ± 5.6 cm. Everyone was informed about the research before the start of the experiments via an information letter and all signed informed consent. Subjects were included when they had no experience with vibrotactile and electrotactile stimulations and did not have any sensory or skin problems of the arm. The study protocol has been approved by the local medical ethical committee (Medisch Ethische ToetsingsCommissie Twente).

B. Experimental Setup

A virtual representation of an opening and closing hand [see Fig. 1(a)] was built in Labview (Labview Inc., 2009b, National Instruments, Austin, TX) to block the normal proprioceptive pathways, thereby enabling the participation of healthy subjects. The hand opening was controlled by the scroll wheel of an adjusted computer mouse. The “rotation clicks” were removed from the scroll wheel to avoid mechanical cues relating the mouse scroll to the hand opening. Furthermore, a randomly varying gain between the level of mouse scrolling and the hand opening was used to further avoid cues about the hand opening related to the mouse scrolling.

Eight circular objects with varying object sizes were simulated within the Labview environment and displayed in random order [see Fig. 1(a)]. A grasping task consisted of the display of an object and an open hand, after which the subject had to change the hand opening through scrolling, to a position which fitted the object correctly. When the hand opening was held constant for 2 s, the task was completed and another object appeared. In the visual feedback conditions, the hand and the object were visible during the whole task. For the nonvisual feedback conditions, only the object was shown shortly at the start of a new grasping task to inform the subject about the object to grasp, but not providing any visual information about the opening of the hand. For each experimental condition, 45 objects were presented, of which the first five objects were applied to get acquainted to the new condition and were not used for further analysis. All hand positions over the whole grasping motion were stored by the program.

C. Vibrotactile and Electrotactile Stimulation

Vibrotactile feedback was provided by an array of eight small commercially available coin motors (Ineed, China). These motors have been used in earlier studies on vibrotactile feedback [13] and were chosen because of their ease of use, their small size, and low costs. The coin motor consists of a rotating inner mass, which stimulates in tangential direction to the skin. The frequency and force of stimulation are coupled and dependent on the characteristics of the skin to which it is attached. The driving current was primarily set to 44 mA for every single vibrator in each experiment, which resulted in clearly tangible, but comfortable sensations. Stimulation amplitudes were adjusted manually, if necessary, to create equally perceived amplitudes of stimulation for each stimulator. The control unit for the array of stimulators was custom build and connected to a National Instruments DAQ system (NI USB-6211, National Instruments, Austin, TX), which was controlled by a Labview syntax, incorporated in the Labview setup. The stimulators were attached to the skin by double-sided adhesive rings (EEG Kleberinge, T06, MedCat, Erica, The Netherlands).

Electrotactile feedback was provided by an array of eight small surface electrodes (Blue sensor BRS, Ambu, Ballerup, Denmark) controlled by another custom build control unit (Octostim) and via Bluetooth the stimulation commands are send from the Labview setup to the control unit. A counter electrode (anode) was placed at the wrist. Before starting the experiments with electrotactile feedback, sensation and comfort thresholds were determined quickly for each electrode. The stimulation amplitude was increased in steps of approximately 0.035 mA and time intervals of 0.5 s until the subject felt the stimulation and pressed the stop button. The resulting amplitude was stored as the sensation threshold. After 1.5-s rest, the amplitude was increased again by the same steps and the subject was asked to press the stop button when the stimulation was not comfortable anymore. The resulting amplitude was called the comfort threshold. The stimulation amplitude for the experiment was determined at 60% between the sensation and comfort threshold. A 60% threshold was chosen to get clear, but certainly not painful, sensations and was based on experience in earlier experiments. The stimulation amplitude was checked for every electrode and adjusted if necessary to get an equal sensation for all electrodes.

D. Feedback

Feedback was applied on the same arm as used for giving control input to the simulated hand, which was their dominant arm in computer use. The hand opening was fed back to the subjects by activation of the corresponding stimulator. The hand opening was discretized to eight steps, corresponding to the eight

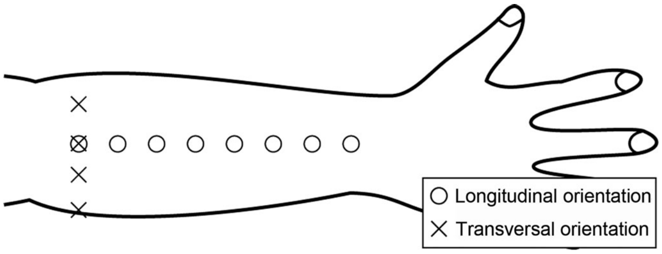

Fig. 2. Schematic overview of the array orientations on the forearm.

stimulators of the array placed on the arm of the subjects. When a hand position was reached, only one of the stimulators was activated and vibrated until further movement of the hand. The stimulators were placed either in a longitudinal or transversal configuration (see Fig. 2). For the longitudinal configuration, the stimulators were placed between the elbow joint and the wrist at the dorsal side of the forearm. Activation of the stimulator closest to the wrist corresponded to a fully closed hand. In the transversal configuration, stimulators were placed around the forearm. To create the largest distance between stimulators, the array was placed at the largest circumference of the forearm, but at least 3 cm from the elbow joint. The distance between the stimulators was equally spread and marked on the arm to use the same positions for both types of stimulation. For patients, the stimulators in the longitudinal configuration were placed on the dorsal side of the stump, with equal interstimulator distances as for the transversal orientation, which led to a number of stimulators (3, 3, and 6 for the patients) crossing the elbow and placement on the upper arm.

Besides the continuous feedback, in some experimental conditions, also feedback was provided when the hand opening corresponded exactly to the size of the shown object, which is referred to as touch feedback. This feedback was given by an extra stimulator or electrode. This stimulator was placed on the forearm of the subject between the elbow joint and the wrist. It was placed on the dorsal side when the array was placed transversally and on the ventral side of the forearm when the array was placed in the longitudinal orientation. The amplitude of stimulation of the single vibrotactile stimulator was the same as for the stimulators in the array and the amplitude of the single electrotactile stimulator was determined by the same procedure as used for the array electrodes as described before. The extra stimulator was activated simultaneously with one of the stimulators in the array, during the whole period the hand was at the correct position.

E. Experimental Conditions

The grasping tasks, consisting of grasping 45 objects, were performed under four different feedback conditions for both types of stimulation and both array orientations (see Table I). The order of the type of stimulation applied and the order of array orientation were randomly chosen beforehand. Both array orientations were applied subsequently for one type of stimulation to reduce the time needed to switch between stimulation types.

TABLE I
SUMMARY OF THE FOUR DIFFERENT FEEDBACK CONDITIONS USED IN THE EXPERIMENT

	Condition name	**Content**
1	Visual feedback	The virtual object and hand are visible during the whole grasping task and no other feedback is given
2	Hand opening feedback	Only the virtual object is shown for a short period, but the hand opening is fed back by activation of the corresponding stimulator
3	Hand opening & touch feedback	Comparable to hand opening feedback, but an extra stimulator is activated when the virtual hand exactly grasps the object
4	No feedback	No feedback about the hand opening is provided and the virtual object to be grasped is only shown shortly at the start of the task

F. Validation on Patients

Based on the results from the healthy subjects, a smaller part of the protocol was executed as validation on patients. Stimulation parameters showing the largest difference in performance were selected, but not when the performance was worse than the nonfeedback situation. For every parameter setting, the visual and the hand opening feedback situation were evaluated and the nonfeedback situation was performed once at the end of the experiment.

G. Outcome Parameters and Statistical Analysis

For every grasping task performed in a certain experimental condition, the time needed to perform the task was recorded. This value comprises the time taken to reach the 40 objects, while the 2 s of object holding were left out. Furthermore, the hand opening in the constant holding phase and the presented object size were compared. Based on this, the percentage of correct hand openings and the mean absolute deviation from the correct hand opening were calculated. Finally, also the percentage of hand openings that only deviated up to one position from the correct hand opening was calculated. This last parameter was chosen to provide an additional accuracy measure which is less strict. A repeated measures analysis of variance (ANOVA) analysis was performed in SPSS (PASW Statistics 18, IBM, Armonk, NY) to evaluate the differences in outcome parameters. The type of stimulation (vibrotactile or electrotactile), the feedback condition (visual, hand opening, hand opening and touch, and no feedback), and the orientation of the stimulator arrays (longitudinal or transversal) were used as the within subjects variables. In case of significant differences ($p < 0.05$), *post hoc* Student *t*-tests were performed for all possible combinations within each factor. A Bonferroni correction was applied when multiple tests were conducted.

III. RESULTS

The results on healthy subjects will be presented first. At the end of this section, the validation results in three patients will be shown.

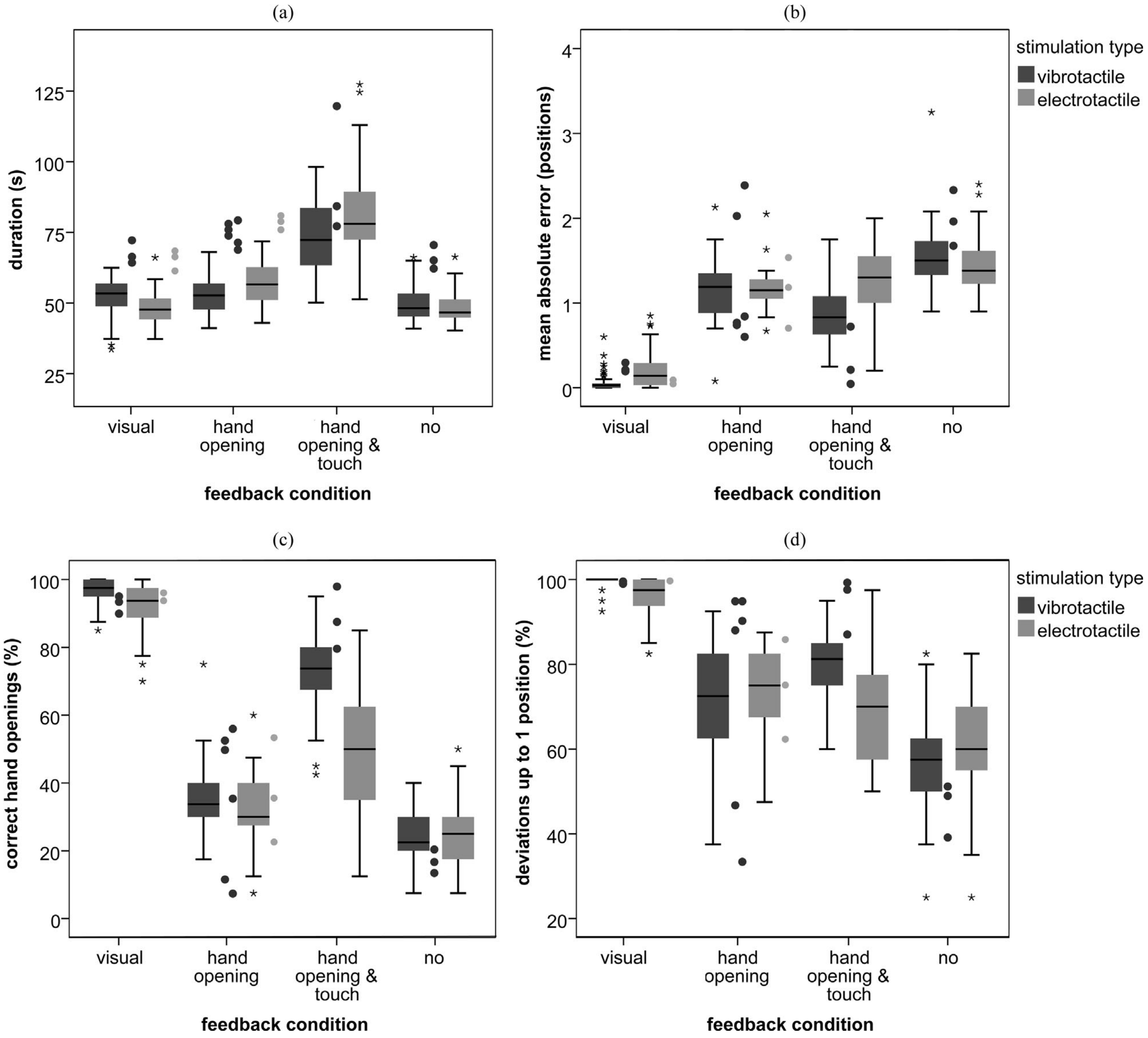

Fig. 3. Distribution of (a) the duration of the tasks, (b) the mean absolute error, expressed in positions, (c) the percentage correct hand openings, and (d) the percentage deviations up to one position, categorized per feedback condition (see Table I) and grouped per type of stimulation for healthy subjects. Patient results are shown in dots next to the bars per feedback condition and for all four parameters. For feedback through vibrotactile stimulation, patient results are shown for both the transversal (left column) and longitudinal (right column) oriented array.

A. *Descriptive Statistics*

The duration of a single task, the mean absolute error, the percentage correct hand openings, and the percentage hand openings deviating up to one position are presented in boxplots [see Fig. 3(a)–(d)]. Median values of the data of all 15 healthy subjects are represented by the thick horizontal lines, the borders of the boxes are the 25th and 75th percentiles and the whiskers represent the minimum and maximum values.

Asterisks indicate the outliers with values larger than 1.5 times the interquartile range from the box edge. Data are separated for both types of stimulation (vibrotactile and electrotactile), but combined for the orientation of the stimulator arrays.

A large spread in data is seen over the different subjects. Further statistical analysis is, therefore, performed by a repeated measures procedure. Repeated measures ANOVA was performed over all data for all four outcome parameters, with the orientation of the stimulator arrays, type of stimulation, and feedback condition as the different factors involved in the analysis. Next, the results of this ANOVA analysis and the necessary *post hoc* tests are described for all factors separately.

B. *Orientation of the Stimulator Arrays*

The distance between the stimulators was almost comparable for both array orientations (3.9 cm for the longitudinal orientation compared to 3.8 cm in the transversal configuration). A

TABLE II
p-VALUES OF REPEATED MEASURES ANOVA FOR EACH OUTCOME PARAMETER WITH TYPE OF STIMULATION AS FACTOR, PER FEEDBACK CONDITION SEPARATELY

Feedback	**Duration**	**Percentage correct**	**Mean error**	**Percentage error ≤ 1**
Hand opening	p=0.024*	p=0.283	p=0.771	p=0.291
Hand opening & touch	p=0.16	p<0.001*	p=0.001*	p=0.002*
No	p=0.523	p=0.343	p=0.397	p=0.389

* indicates cases where vibrotactile stimulation performed significantly better at a significance level of 0.05.

paired *t*-test has shown that these differences were not statistically different ($p = 0.2$).

Resulting from the repeated measures ANOVA, no significant differences for all four parameters were found for the orientation of the array on the forearm ($p = 0.37$ to 0.92).

C. Type of Stimulation

No subjective measures, like questionnaires, to compare vibrotactile and electrotactile stimulations were used. However, several subjects spontaneously reported that vibrotactile stimulation was perceived as being more comfortable. Furthermore, electrotactile stimuli were often reported as painful (after threshold determination) and had to be adjusted, which never happened for vibrotactile stimuli.

The repeated measures ANOVA showed significant differences for all four outcome parameters for the type of stimulation. The performance in the grasping tasks is significantly better when feedback is given via vibrotactile stimulation, expressed in a shorter duration of the task, lower mean errors, and higher percentages of correct hand openings compared to electrotactile stimulation. A significant interaction component with the feedback condition was also shown, and therefore, the effects of the type of stimulation on the performance parameters were analyzed by repeated measures ANOVA for each feedback condition separately. The results of this comparison between vibrotactile and electrotactile stimulations were expressed in the *p*-values for significance and summarized in Table II.

When only hand opening feedback is provided, there is no difference in performance between feedback through vibrotactile or electrotactile stimulation, while vibrotactile stimulation performs much better when extra feedback is added about the exact grasping. Although there were no differences in the direct performance parameters, the duration of the tasks performed with vibrotactile stimulation was significantly lower compared to electrotactile stimulation in the situation with only hand opening feedback.

D. Feedback Conditions

The results of the repeated measures ANOVA show significant differences in performance over the four feedback conditions (visual, hand opening, hand opening and touch, and no feedback) for all four performance parameters ($p \leq 0.001$). A significant interaction component with the type of stimulation was also seen; therefore, repeated measures ANOVA was performed per type of stimulation, which showed significant influences of feedback condition for both types of stimulation for all four outcome parameters. Therefore, the *post hoc* analyses were performed for both types of stimulation separately. To compensate for the repeated execution of *post hoc* tests, Bonferroni correction was applied. The original significance level (0.05) is divided by the number of tests performed (6). The corrected significance is now 0.008.

No differences were found for the duration of the tasks in conditions without any feedback compared to tasks where visual feedback is available. However, the addition of feedback through electrotactile stimulation increases the duration of the tasks significantly ($p < 0.001$) compared to the nonfeedback and visual feedback conditions, which is also the case for the addition of touch feedback ($p < 0.001$ for electrotactile stimulation as well as for vibrotactile stimulation). It took the subjects longer to identify the activation of the extra stimulator or they needed more time to reach the correct hand opening.

The percentages hand opening with deviations up to one position show a significant increase in performance when feedback is added. The best performance is shown for the visual feedback condition, followed by the hand opening and touch feedback condition. The performance in conditions with hand opening feedback is significantly better compared to the nonfeedback conditions ($p = 0.001$ and $p = 0.003$ for electrotactile and vibrotactile stimulations, respectively). For the electrotactile stimulation feedback conditions, no increase in performance is seen for the addition of touch feedback compared to the hand opening feedback condition ($p = 0.135$ compared to $p = 0.007$ for vibrotactile hand opening and touch feedback). The same conclusions can be drawn for the other outcome parameters, the mean absolute error, and the percentage of correct hand openings, which showed comparable *p*-values.

E. Validation on Patients

The stimulation conditions used in the validation protocol were 1) the transversal oriented vibrotactile array, 2) the longitudinal oriented array, 3) vibrotactile touch feedback with the transversal oriented array, and 4) the transversal oriented electrotactile array. The results are plotted in Fig. 3 for each patient separately and each feedback condition. On average, the performance parameters were highly comparable with healthy subjects and for the transversal vibrotactile array even somewhat higher (up to 16%). Furthermore, the same trends were seen, specifically an increase in performance with feedback and a higher duration for electrotactile compared to vibrotactile feedback and for touch feedback. However, the duration of all tasks was higher for the patients (70.6 compared to 55.4 s).

IV. DISCUSSION

A. Orientation of the Stimulator Arrays

The distance between the stimulators was not significantly different between both orientations of stimulation. Therefore, performance parameters could be compared between these two orientations. The longitudinal orientation was selected for this study because it is possibly more functional and has a more intuitive relation to the control of the hand and the orientation of the muscles used to close and open the hand. However, the forearm stump could be too short to apply an array of eight stimulators in a longitudinal direction, which is not the case for the transversal oriented array.

Our results showed no differences in performance for the different orientations of the stimulator array. However, differences in distance and location perception were found by Green between both orientations of pressure stimuli [14], and in a study by Higashiyama and Hayashi better localization performance of seven electrotactile stimuli was seen for transversal oriented arrays [15]. In addition, Cody *et al.* showed that the spatial acuity is significantly better for stimulators oriented transversal on the arm compared to longitudinal [16]. These findings were explained by the orientation of the receptive fields of the mechanoreceptors in the forearm. These fields are smaller in the transversal direction compared to the longitudinal direction. However, no effects of this difference were found in our study. It is also known that the localization of vibrotactile stimuli, which is also used in these experiments, is better for stimulators close to an anatomical landmark [17]. Some of the longitudinal oriented stimulators were at the ends close to these landmarks (wrist and elbow), but for the transversal orientations these effects are equal over the whole length. This could have counteracted possible differences in performance caused by the asymmetry in receptive fields. Furthermore, the experiments of Cody *et al.* were performed with a von Frey hair stimulus at shorter interstimulus intervals, which also made comparison with our study difficult.

The mean distance between the stimulators was less than 4 cm, which is within the spatial acuity range found in the literature for different body locations (2–4 cm) [18]. However, most psychophysical studies were performed using pressure stimuli instead of vibrotactile stimuli and not for this number of stimulators. Higashiyama and Hayashi used an array with seven electrodes on the volar side of the forearm and found localization errors that were much smaller than the interelectrode distance, used in our study [15]. In a study by Cholewiak *et al.* [19], it was shown that the maximum number of stimulators to be distinguished on the trunk was seven. The optimal number of stimulators to be used in an array on the forearm should be further investigated, where a tradeoff should be made between the localization performance and the amount of information (number of hand opening levels for example) to be fed back by the stimulation.

B. Type of Stimulation

A significant effect was seen for the type of stimulation. In general, all performance outcome parameters were better for the experimental conditions with feedback through vibrotactile stimulation compared to electrotactile stimulation. The only exceptions were the hand opening feedback conditions without touch feedback. In these cases, the percentages of correct hand openings, the mean error, and the percentages deviations up to one position were comparable for both types of stimulation, indicating the same level of accuracy that could be achieved. However, the time needed to perform the grasping tasks was significantly higher for the electrotactile stimulation condition, which also impedes the performance, because this will slow down the handling speed of the subjects. This difference in duration can be caused by lower onset times of the vibrotactile stimulators or because it takes longer to recognize a specific electrotactile stimulator in an array. However, these hypotheses have not been investigated further or been described earlier. In recent research, there is already a clear preference for the use of vibrotactile stimulation over electrotactile stimulation. Vibrotactile stimulation has been indicated as a more comfortable stimulation method [13] and the small range between sensation and pain thresholds with electrotactile stimulation was also indicated as a reason to prefer vibrotactile stimulation over electrotactile stimulation [20]. However, it has not been objectively investigated before whether the performance with vibrotactile stimulation is better than with feedback through electrotactile stimulation.

The addition of an extra stimulator for touch feedback further increases the performance in the grasping tasks when vibrotactile feedback is provided, but the performances stay on a constant level for electrotactile stimulation. This was also indicated by the subjects, who stated that it was difficult to experience the difference between the activation of one of the electrodes within the array and activation of the extra electrode. However, the distance between the stimulator array and the extra stimulator was always larger than the interstimulator distance of the array. No clear differences in spatial acuity and localization can be found in the literature for electrotactile and vibrotactile stimulation, but this study showed that differentiation problems can occur when a single electrotactile stimulator is placed too close to an array of stimulators and activated at the same moment. Increasing the stimulation amplitude might enhance the differentiation between the array and the extra stimulator, but also increases the likelihood of painful stimuli.

The currently available vibrotactile stimulators are mostly not suitable for applications in forearm prostheses, because of their relatively large size and high power consumption. The coin motors, as used in this study and in a study by Pylatiuk *et al.* [13], can be a good alternative, because of the small size and low costs. A comparison of localization performance with a dense array of these coin motors and larger C2 tactors showed no differences between these stimulators [21].

However, the actual performance and application in forearm prostheses should be an important subject of further research.

C. Feedback Condition

The best results for the percentages of correct hand openings and the mean absolute errors were shown for the hand opening and touch feedback conditions. However, the duration of the tasks was also significantly increased with the addition of feedback through electrotactile stimulation and the use of the extra stimulator, which is in line with the recent literature showing that the addition of proprioceptive feedback increases the performance, but at the cost of a longer task execution duration [9], [22]–[24]. Vibrotactile feedback enhances the performance in grasping tasks without lengthening of the task duration and can be seen as a better method to provide hand opening feedback compared to feedback through electrotactile stimulation or the use of an extra stimulator.

The percentages of correct hand openings that can be achieved by the addition of vibrotactile or electrotactile feedback are quite low, between 30% and 50%, especially when compared to the visual condition where percentages of almost 100% can be reached. However, the increase in performance that can be achieved compared to the nonfeedback condition is significant. Furthermore, it was shown that the desired hand opening was reached exactly or with a deviation of one position in almost 80% of the cases. This shows that the addition of hand opening feedback significantly improves the accuracy in a grasping task. In a study by Blank *et al.*, it was already shown that feedback about the hand opening improves the targeting accuracy compared to nonfeedback conditions [25]. However, they have used proprioception motion feedback, moving the index finger according to the movements of a virtual finger and controlled by the force applied by the thumb, which cannot be used by patients. The aim of their study was to investigate the general effects of proprioceptive feedback. They concluded that proprioceptive feedback indeed increases the accuracy in coarse movements, but the addition of tactile feedback would be needed to improve the accuracy in more precise movements. This was confirmed by the results of our study in which the percentage of correct hand openings could still be significantly improved by the addition of an extra stimulator, activated when the virtual object was touched. This touch feedback may be combined with feedback about the gripping force and thereby further increase the performance in grasping tasks.

D. Validation on Patients

The performances of patients in virtual grasping tasks were comparable to the results with healthy subjects, despite the possible differences in sensibility of the stumps and the fact that control of the hand was performed with the other hand. The placement of a number of stimulators on the upper arm for the longitudinal orientation did not influence the results and can be a solution for patients with short stumps. In actual use, the prosthesis will be controlled by EMG. In the current study, EMG control was replaced by scroll wheel control in order to focus on the influence of tactile feedback on performance, avoiding the confounding effect of EMG control, which may be very variable amongst. However, in future studies, EMG control needs to be included. An increase of duration of the tasks was seen in comparison to the healthy subjects, which could be caused by the difference in experience with experimental settings and computer skills. The healthy subjects all did participate in experimental studies before and all patients did not. However, it is also possible that patients needed more time to interpret the stimuli.

E. Experimental Setup

Because of the relatively small number of patients available, the largest part of the experiments is performed on healthy subjects. Therefore, a virtual environment, showing an opening and closing hand, was built to circumvent the intact proprioceptive pathways of the healthy subjects. The hand was controlled by the scroll wheel of a computer mouse, which is not comparable to the myoelectric control as used in today's prostheses. This approach was chosen to avoid the long training period needed to learn the myoelectric control and to avoid the large variability in the within-subject performances for this control method. The muscles used to control the computer mouse are to some extent comparable to those used to open and close the hand. Furthermore, it also ensures that no feedback about the hand opening could be derived via channels other than the stimulation provided. To further optimize this, the click mechanism was removed from the scroll wheel of the computer mouse and a variable gain between the scrolling movement and the hand movement was added. The success of this approach was shown in the results for the nonfeedback conditions. The percentages of correct hand openings were around 20%, which coincides largely with the percentages expected with straight guessing. The percentages are somewhat higher, due to the known endpoints of the hand movement when the hand is fully closed or opened.

V. CONCLUSION

It is shown that feedback about the hand opening through vibrotactile and electrotactile stimulations improves the performance in grasping tasks for healthy subjects as well as for potential users, being forearm amputees using myoelectrically controlled prostheses. This performance is expressed in an increase of correct or nearly correct hand openings and a decrease in absolute errors. Future applications of vibrotactile stimulation are preferred over electrotactile stimulation, because the duration of the tasks is undesirably increased with electrotactile stimulation. The addition of touch feedback leads to even more accuracy for vibrotactile feedback, but increases the duration of the grasping tasks.

ACKNOWLEDGMENT

The authors would like to thank J. Olsman for his help with the recruitment of the patients and thank all subjects for their participation in this study.

REFERENCES

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

[2] I. Dudkiewicz, R. Gabrielov, I. Seiv-Ner, G. Zelig, and M. Heim, “Evaluation of prosthetic usage in upper limb amputees,” *Disability Rehabil.*, vol. 26, pp. 60–63, 2004.

[3] J. L. Pons, R. Ceres, E. Rocon, D. Reynaerts, B. Saro, S. Levin, and W. Van Moorleghem, “Objectives and technological approach to the development of the multifunctional manus upper limb prosthesis,” *Robotica*, vol. 23, pp. 301–310, 2005.

[4] E. Biddiss and T. Chau, “Upper-limb prosthetics—Critical factors in device abandonment,” *Amer. J. Phys. Med. Rehabil.*, vol. 86, pp. 977–987, 2007.

[5] B. Peerdeman, D. Boere, H. J. B. Witteveen, R. Huis in ‘t Veld, H. J. Hermens, S. Stramigioli, H. Rietman, P. Veltink, and S. Misra, “Myoelectric forearm prostheses: State of the art from a user-centered perspective,” *J. Rehabil. Res. Dev.*, vol. 48, pp. 719–738, 2011.

[6] R. W. Mann and S. D. Reimers, "Kinesthetic sensing for EMG controlled boston arm," *IEEE Trans. Man-Mach. Syst.*, vol. MM-11, no. 1, pp. 110–115, Mar. 1970.

[7] G. S. Dhillon and K. W. Horch, "Direct neural sensory feedback and control of a prosthetic arm," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 4, pp. 468–472, Dec. 2005.

[8] R. E. Prior and J. Lyman, "Electrocutaneous feedback for artificial limbs. Summary progress report. February 1, 1974, through July 31, 1975," *Bull. Prosthet Res.*, pp. 3–37, 1975.

[9] K. J. Kuchenbecker, N. Gurari, and A. M. Okamura, "Effects of visual and proprioceptive motion feedback on human control of targeted movement," in *Proc. IEEE 10th Int. Conf. Rehabil. Robot.*, Noordwijk, The Netherlands, 2007, pp. 513–524.

[10] A. Blank, A. M. Okamura, and K. J. Kuchenbecker, "Effects of proprioceptive motion feedback on sighted and non-sighted control of a virtual hand prosthesis," in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Reno, NV, 2008, pp. 141–142.

[11] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 1, pp. 1–16, Jan. 1991.

[12] C. Antfolk, C. Balkenius, G. Lundborg, B. Rosen, and F. Sebelius, "A tactile display system for hand prostheses to discriminate pressure and individual finger localization," *J. Med. Biol. Eng.*, vol. 30, pp. 355–359, 2010.

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

[14] B. G. Green, "The perception of distance and location for dual tactile pressures," *Perception Psychophys.*, vol. 31, pp. 315–323, 1982.

[15] A. Higashiyama and M. Hayashi, "Localization of electrocutaneous stimuli on the fingers and forearm—Effects of electrode configuration and body axis," *Perception Psychophys.*, vol. 54, pp. 108–120, Jul. 1993.

[16] F. W. J. Cody, R. A. D. Garside, D. Lloyd, and E. Poliakoff, "Tactile spatial acuity varies with site and axis in the human upper limb," *Neurosci. Lett.*, vol. 433, pp. 103–108, Mar. 2008.

[17] R. W. Cholewiak and A. A. Collins, "Vibrotactile localization on the arm: Effects of place, space, and age," *Perception Psychophys.*, vol. 65, pp. 1058–1077, 2003.

[18] B. Cheung, J. B. F. Van Erp, and R. W. Cholewiak, "Anatomical, neurophysiological and perceptual issues of tactile perception," in *Tactile Displays for Orientation, Navigation and Communication in Air, Sea and Land Environments*. Neuilly sur Seine, France: NATO Res. Technol. Org., 2008.

[19] R. W. Cholewiak, J. C. Brill, and A. Schwab, "Vibrotactile localization on the abdomen: Effects of place and space," *Perception Psychophys.*, vol. 66, pp. 970–987, Aug. 2004.

[20] L. A. Jones and N. B. Safter, "Tactile displays: Guidance for their design and application," *Human Factors*, vol. 50, pp. 90–111, 2008.

[21] R. W. Cholewiak and K. Beede, "The representation of space through static and dynamic tactile displays," presented at the Proc. Virtual Reality Int. Conf. Conjunction Human Comput. Interaction, Las Vegas, NE, 2005.

[22] C. E. Stepp and Y. Matsuoka, "Relative to direct haptic feedback, remote vibrotactile feedback improves but slows object manipulation," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, pp. 2089–2092.

[23] C. Bark, J. Wheeler, and S. Premakumar, "Comparison of skin stretch and vibrotactile stimulation for feedback of proprioceptive information," in *Proc. IEEE/VR Symp. Haptic Interfaces*, 2008, pp. 71–78.

[24] J. Wheeler, K. Bark, J. Savall, and M. Cutkosky, "Investigation of rotational skin stretch for proprioceptive feedback with application to myoelectric systems," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no. 1, pp. 58–66, Feb. 2010.

[25] A. Blank, A. M. Okamura, and K. J. Kuchenbecker, "Identifying the role of proprioception in upper-limb prosthesis control: Studies on targeted motion," *Trans. Appl. Perception*, vol. 7, no. 3, pp. 1–23, 2010.

Heidi J. B. Witteveen was born in Apeldoorn, The Netherlands, in 1983. She received the M.Sc. degree in biomedical engineering from the University of Twente, Enschede, The Netherlands, in 2007, where she is currently working toward the Ph.D. degree in biomedical engineering.

Her M.Sc. thesis was on the assessment of spasticity in spinal cord injured patients via long-term EMG recordings. Her research interests include myoelectric prostheses and electro- and vibrotactile feedback systems for upper-extremity prostheses.

Ed A. Droog was born in Delft, The Netherlands, in 1954. He studied electrical engineering at a technical institute in Hengelo, The Netherlands.

From 1978 to 1982, he was with the "Stadsmaten" Hospital, Enschede, The Netherlands. In 1982, he joined the Biomedical Engineering Division of the University of Twente, Enschede. His main research interests include the development of analogue and digital hardware for the various scientists in the division.

Johan S. Rietman was born in Almelo, The Netherlands, in 1960. He received the M.D. degree and Ph.D. degree in medicine from the University of Groningen, Groningen, The Netherlands, in 1990 and 2005, respectively.

He is the Director of the research institute Roessingh Research and Development, Enschede, The Netherlands. He is also a Professor of rehabilitation medicine and technology in the Department of Biomechanical Engineering, University of Twente, Enschede. His research focuses on the clinical use of technology in restoration of functions in patients with neurological disorders and patients with amputations of upper and lower extremities.

Peter H. Veltink (SM'06) was born in Groenlo, The Netherlands, in 1960. He received the M.Sc. (*cum laude*) degree in electrical engineering and the Ph.D. degree in the area of electrical nerve stimulation both from the University of Twente, Enschede, The Netherlands, in 1984 and 1988, respectively.

He is currently a Professor of technology for the restoration of human function and chairman of the Biomedical Signals and Systems Department, Institute for Biomedical Technology and Technical Medicine, University of Twente. He is the (co)author of more than 100 peer-reviewed journal papers and many peer-reviewed conference papers. His research is in the areas of biomechatronics which includes artificial motor control, ambulatory sensing of human motor control, specifically ambulatory movement and force sensing, with applications in rehabilitation medicine and biomechanics; and in the areas of neural engineering encompassing neurostimulation for neuromodulation, including deep brain stimulation, neurocardiology, stimulation of spinal cord, and cortex for suppression of pain.

Dr. Veltink is an Associate Editor for the IEEE TRANSACTIONS OF NEURAL SYSTEMS AND REHABILITATION ENGINEERING and reviewer for many scientific journals. He was the Treasurer of the International Functional Electrical Stimulation Society from 1996 to 2001, and has been the Chairman of the Benelux IEEE-EMBS chapter since 2005. He received the Royal Shell Stimulating Prize for his contribution to the rehabilitation-engineering field in 1997 and the Decade of Partnership Award from the company Xsens in 2010. He has been the Scientific Coordinator of three EU research training networks (ARNESCO, NEUROS, and neuralPRO) and coordinates the EU project INTERACTION since November 2011.