

# Vibrotactile stimulation of the upper leg: Effects of location, stimulation method and habituation

E.C. Wentink, A. Mulder, J.S. Rietman, P.H. Veltink

**Abstract-** In this study vibrotactile stimulation of the upper leg and its usability for feedback was tested. Three experiments were performed on ten healthy subjects using pager motors. The first experiment was to test the perception of the vibration at different frequencies and at different locations of the upper leg. The second experiment tested the ability of subjects to estimate location and number of stimuli in an array. In addition it was evaluated whether simultaneous or sequential stimulation is better interpretable. Thirdly the habituation of the vibration was determined. The experiments showed that vibrotactile stimulation is well perceived and can be useful in providing feedback on the upper leg. Further experiments are needed to determine the effectiveness of vibrotactile stimulation for feedback in trans-femoral prostheses.

**Keywords:** trans-femoral amputees, feedback, vibrotactile stimulation, lower extremity.

## I. INTRODUCTION

The perception of vibrotactile stimulation of the upper extremities has been widely studied [3,4,8,9,11]. Vibration is also used as a feedback method in several studies, such as the tactile suit[5], a tongue display unit to allow blind people to “see”[1], balance control[12] and an arm prosthesis, the “boston arm”[9]. For trans-femoral amputees (TFA) however, little research has been done on feedback. Fan et al. [6] used pneumatically actuated balloons to provide feedback, but the system was slow. Buma et al. [2] investigated electrotactile stimulation of the upper leg and found that during continuous stimulation the perception of the stimuli is strongly effected by habituation. Stimulation amplitudes were high, which had reddening and irritation of the skin as a consequence[2,10]. Vibrotactile stimulation may be a useful alternative for feedback on the lower extremities. In vibrotactile stimulation three types of mechanoreceptors in the skin can play a role, Merkel disks, Meissner’s corpuscles and Pacinian corpuscles. Each with its own specific responsive frequency range,

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5-15Hz, 20-50Hz and 60-400Hz respectively[7]. The best detected frequency for skin vibration lies around 250Hz [4,7,8,11]. Higher frequencies (200Hz) also have a higher discriminable frequency increment ( $\Delta f = \sim 20\text{Hz}$ ) than lower frequencies (at 20Hz  $\Delta f = \sim 5\text{Hz}$ ), for the fingertip and the forearm[8].

Several studies have been performed with vibrotactile stimulation on the upper extremities, also using arrays. One study showed that when vibrating the forearm in an array of 7 vibrators, subjects correctly identified 50% of the stimuli locations[3]. The outer stimulus locations were better detected than those in the middle of the array. Increasing the distance between the stimulators from 25mm to 50mm increased the percentage of correctly identified locations[3]. Elderly subjects however, scored lower in the percentage of correct detections[3].

Vibrotactile stimulation of the upper leg has scarcely been studied and we would like to know if this stimulation method may be suitable for the use as a feedback method in trans-femoral prosthesis (TFP). Weinstein [13] found, using pressure tests, that the ventral side of the thigh, one of the least sensitive body parts, has a two point discrimination threshold of 45mm. Cholewiak et al. [4] performed similar tests using two point vibrations and found that the perceived distance increases if the vibration exceeded the two-point discrimination threshold, in both the transverse and longitudinal direction[4,13], but little else is known on vibrotactile stimulation of the upper leg.

For feedback to be effective, the user must feel and interpret the signal. In this study we therefore performed three tests to determine the effect of vibrotactile stimulation on the upper leg and its suitability for feedback, using 8 pager motors. The first test was to determine the effect of location of the vibration and the perception of the stimuli. The second experiment was the localization of active vibrators in an array using two different stimulation methods, sequential and simultaneous (interpretability). The third experiment was to test for habituation during continuous stimulation. From this we determined the suitability of vibrotactile stimulation for feedback on the upper leg.

## II. METHODS

### A. Setup

For the experiments an 8-channel vibrator was used. The vibrator consists of 8 small pager motors(Fig. 1a), which can be individually controlled using a DA-converter by National Instruments. The pager motors are 1 cm in diameter and have a frequency range of 30 to 80Hz, frequency and amplitude are coupled. A 3D accelerometer placed on one of the pager motors was used to determine the frequency. Ten healthy

subjects participated in the study for experiments one and two, eight healthy subjects for experiment three. An informed consent was obtained before the experiments according to the ethical principles of the Helsinki convention, and the experiments were approved by the local ethics committee.

### B. Experiment 1

Goal of the first experiment was to determine differences in perception of vibration at different frequencies and at different locations of the upper leg. Eight vibrators were placed at the upper leg of the subjects (Fig. 1b). The vibrators were placed in four pairs, about 20 cm apart. One pair at the lateral side, one medially, one posterior and one anterior, to cover the whole area of the upper leg. It was chosen to apply six frequencies in the frequency range 30-80Hz (10Hz increment) randomly to each vibrator, whereby each frequency was presented three times at each vibrator. Smaller increments were unlikely to be felt [8]. To rate the intensity of a stimulus a visual analog scale (VAS) was used. The VAS consisted of a 10cm long horizontal line with on the left "no sensation" and on the right "strong sensation". Subjects were asked to cross the line according to their sensation, they received a new VAS for each stimulus. The VAS scores were normalized to compare the results for all subjects. It was determined how the VAS scores differed for the different frequencies and for the different locations. A t-test was used to determine if the differences in VAS scores were significant.

### C. Experiment 2

The goal of the second experiment was to determine which stimulation method, sequential or simultaneous stimulation, is best suited when stimulating with an array. It was determined how well the subjects can identify, the number of active vibrators, the position of the vibrator and the distance between them. To prevent long experiments this was done with sequential and simultaneous stimulation for the posterior and anterior side of the upper leg. The array of 8 vibrators was placed in a row, with 2cm between the vibrators, the most proximal one was numbered "1" and the most distal one "8" (Fig. 1c). The subjects received 60 random sets of vibrations at 80Hz (max. sensation) for each condition, whereby for each set one, two or three vibrators were active. For sequential stimulation the vibrators were active one after the other with 200ms in between and for the simultaneous case the vibrators were stimulated at the same time for 200ms.

The subjects were required to select the vibrators which they thought were active for each set. It was determined if the number of applied stimuli equaled the estimated number of stimuli. The performance in detecting the number of active vibrators was determined by calculating the sensitivity and the specificity per number of active vibrators. The sensitivity is the probability that the subjects indicated the correct number of active vibrators. The specificity is the probability that, for a certain number of active vibrators, the subjects correctly indicated that

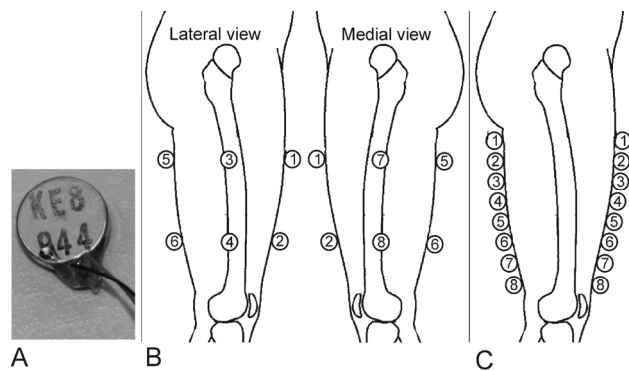


Fig. 1. A. A pager motor as used in the experiments, by J.F. Machinery Co, Ltd. B. locations of the vibrators for experiment 1, C. locations of the vibrators for experiment 2.

this was not the number of active vibrators. The determination of the locations was only performed for those trials where the number of estimated stimuli was equal to the applied number of stimuli. The distances between the applied stimuli were only calculated for those sets of the trials where 2 or 3 stimuli were applied and subsequently identified as such. Due to non-normal distributions (especially for the end vibrators) a Wilcoxon-signed-rank test was for statistic analysis.

### D. Experiment 3

The third experiment was performed to determine habituation when using vibrotactile stimulation. One vibrator was placed in the middle of the anterior side of the upper leg. It was vibrated continuously for 15 min. at 80Hz. The subjects were asked to rate the perceived intensity of the stimulus every 40 seconds on a VAS of 20cm, and were asked to rate the first stimulus in the middle. From this the half-life time was calculated, this is the time between start of the stimulation and when the stimulation reached half the original VAS score. The half-life was calculated using a fit of the data to estimate the time where the VAS was only half the original value. An exponential fit was used as in most trials the VAS decayed exponential to an asymptote between 0 and 1. The asymptote was subtracted from the initial value for calculation of the half-life time.

## III. RESULTS

### A. Experiment 1

Fig. 2 shows the results of the first experiment for all 10 subjects together for the four different locations. For all locations can be seen that when the frequency increases, the VAS also increases. The anterior side and the lateral side show only a small increase in VAS as the frequency increases, with a high variation. The differences in VAS between 30 and 80Hz of the lateral and anterior side do not show significant differences. However, the posterior and medial side of the upper leg gave different results. At both these locations the frequency range of 30-50Hz was poorly perceived, and no significant differences were found. For 50-70Hz frequency range, the VAS increases significantly as the frequency increased. This saturates in the 70-80Hz range, which is not significant. For the posterior and medial side of the upper leg this implies that two frequency ranges can be distinguished, for the anterior and lateral side this is only one frequency

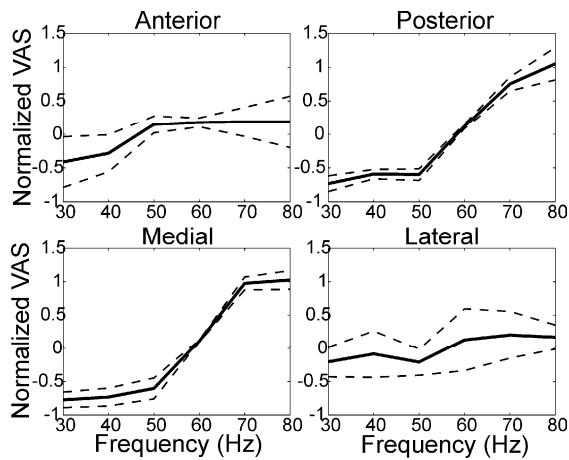


Fig. 2. The normalized VAS as function of the applied frequency, for four different locations. The solid black line is the average per location over all 10 subjects, the dashed line is the SD.

range. For all locations together the VAS also increases as the frequency increases. The increase in VAS in the frequency range 50-70Hz is significant, no further significant differences were found.

### B. Experiment 2

Firstly we determined how the subjects performed in correctly identifying the number of applied stimuli, one, two or three. Table I shows the results of the sensitivity and the specificity of the identified number of applied stimuli, from 10 healthy subjects. From Table I can be seen that in the cases where the stimuli were applied sequentially, the sensitivity and specificity of the estimated number of stimuli is always higher than in the case where the stimuli were applied simultaneously.

Secondly we investigated how well the subjects were able to estimate the location of the stimuli during sequential and simultaneous stimulation at the two different locations of the leg. Fig. 3 shows the applied stimulus location as a function of the estimated stimulus location by the subjects. For the sets with one and two stimuli not all vibrators were active during the experiments, due to the randomization. Therefore, as an example only the results from the trials with three applied stimuli are shown. From Fig. 3 can be seen that in case of sequential stimulation, the median of the location estimate (solid black horizontal line) lies at or near the location at which the stimulus was applied. The diagonal lines show where the medians should lie, if the location is estimated correctly. This is especially the case for three applied stimuli, Fig. 3 A and C. For the simultaneous stimulation the variation is larger and the median of the estimated location does not always coincide with the applied location.

Thirdly we looked at how well the subjects were able to determine the distance between the activated vibrators. Even though they may not estimate the exact location of the applied stimuli correctly, the estimated distance between the stimuli, expressed as number of vibrators in between, could still be correct. Fig. 4 shows the results from the distance estimation, for three stimuli. The

TABLE I  
SENSITIVITY AND SPECIFICITY

	Nr stim	ASeq	PSeq	ASim	PSim
Sens	1	0.93	0.89	0.10	0.75
	2	0.86	0.80	0.53	0.06
	3	0.94	0.86	0.51	0.51
Spec	1	0.99	0.97	0.90	0.90
	2	0.95	0.90	0.59	0.56
	3	0.91	0.87	0.64	0.75

Sens is sensitivity, Spec is specificity, ASeq is anterior sequential, PSeq is posterior sequential, ASim is anterior simultaneous and PSim is posterior simultaneous.

variation for the sequential trials is smaller than for the simultaneous trials, but this is not significant. No differences are seen between sequential and simultaneous stimulation, with respect to distance estimation. For these trials the distances 2-6cm (0-3 vibrators) show a smaller variation in the estimated distances than for the applied distances of 8-12cm (4-6 vibrators).

### C. Experiment 3

To estimate the time where the VAS was half the original value of 10, an exponential fit was applied to the data. Six of the eight subjects showed an exponential decay of the VAS. The other two subjects did not show a decay in the VAS at all, the score fluctuated in both cases, but did not show a trend down or up, no half-life was calculated for these two subjects. The average half-life (SD) of the VAS in the six subjects was 291.8sec (150.8sec). In five of the six subjects the VAS was between zero and one at the end of the experiment. In one subject the VAS decayed exponential, but did not go below three.

## IV. DISCUSSION

The first experiment shows that the higher frequencies (60-80Hz) are better perceived than the lower frequencies (30-50Hz). This coincides with literature[4,7,8,11], but may also be the result of the fact that the amplitude and frequency are coupled for the pager motors; if the frequency increases, the amplitude also increases. For the anterior and lateral side the differences in VAS for different frequencies were less clear than for the posterior and medial side of the upper leg. The posterior and medial side however, showed that the frequencies 30-50Hz were hard to perceive at all, whereas the frequencies 50-70Hz were easy to distinguish from each other. The stimulation frequencies between 60 and 80Hz are perceived best at all locations. The posterior and medial side of the upper leg may be best if frequency modulation is to be used for feedback. However, the results also show that frequency modulation as a way of providing feedback may not be suitable, as the change in frequency is not always noticed. The second experiment shows that sequential stimulation is much better than simultaneous stimulation, when estimating of the number of active vibrators. For the estimation of location and distance however, these differences diminish. Sequential stimulation performs slightly better, but this is not the case for all trials nor is it significant. However, in a spatial presentation of feedback (an array) sequential stimulation is preferred above simultaneous stimulation, due to the better results

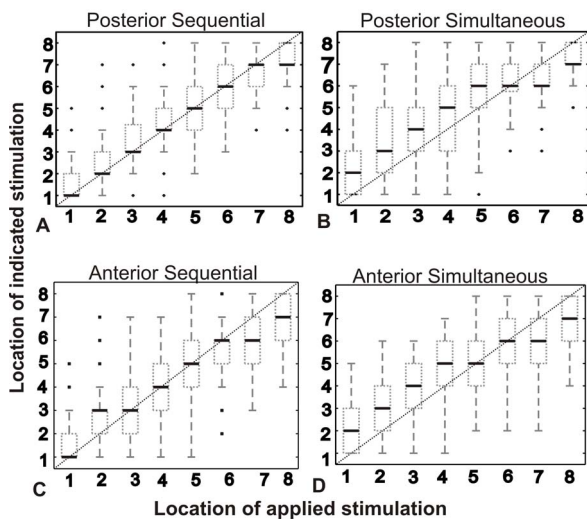


Fig. 3. The applied stimulus location as function of the indicated location by the subjects, for the sets with three stimuli. A and B show the results for stimulation at the posterior side of the leg; A for sequential and B for simultaneous stimulation. Graphs C and D show the results for stimulation at the anterior side of the leg; C for sequential and D for simultaneous stimulation. They are all the results for the sets where three stimuli were applied. The solid horizontal line is the median, the edges of the boxes refer to the 25 and 75 percentiles and the whiskers extend to the extreme data points, excluding the outliers (black dots).

from the estimated number of active vibrators.

The smaller distances were perceived with higher accuracy than the larger distances. This may be explained by the fact that if two vibrators next to each other are active they feel like one active vibrator with an increased amplitude. As the amplitude in this experiment did not change, a change in the amplitude felt by the subjects was probably interpreted as two active vibrators next or close to each other.

The third experiment shows that it takes almost 300 seconds of continuous vibration before the VAS is half of its original value. This is much more than the half-life of, for instance electrotactile stimulation which is about 185 seconds for continuous stimulation[2]. However, some subjects complained after the 15 min, that the vibrator became hot and that it would not be comfortable to keep the stimulation going on for longer. This can be resolved by stimulating intermittently at different locations and not continuously at the same location. Other options are to stimulate at a lower frequency, for instance 70Hz, which did not show a significant lower perception or to use different vibrators. The disadvantages of pager motors were the frequency and amplitude coupling and the low range of available frequencies, vibrators with a larger frequency range may improve the results. Advantages are that they are small, light weight, low in energy consumption and cheap. Further research is needed before it can be implemented into a trans-femoral prosthesis, to enable subjects to interpret rapidly changing dynamic patterns of vibrotactile stimulation at the stump.

From this study we can conclude that vibrotactile stimulation at the upper leg, is suitable for feedback. Sequential stimulation will be most suitable for feedback,

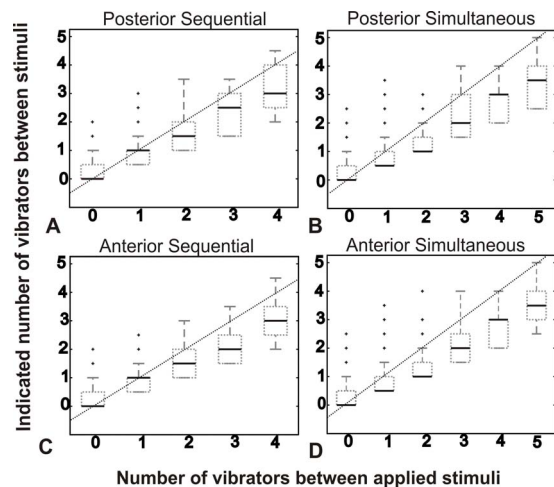


Fig. 4. The applied distance as function of the estimated distance for the sets with three stimuli. A and B show the results for stimulation at the posterior side of the leg; A for sequential and B for simultaneous stimulation. Graphs C and D show the results for stimulation at the anterior side of the leg; C for sequential and D for simultaneous stimulation. The solid horizontal line is the median, the edges of the boxes refer to the 25 and 75 percentiles and the whiskers extend to the extreme data points, excluding the outliers (black dots).

it is better interpretable and avoids habituation. Use of different vibrators may improve the results and may avoid the problem of heat development. The most sensitive locations and therefore the best position to provide feedback appeared to be the medial and posterior side of the upper leg.

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