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Analysis of Vibrotactile Perception via e-Textile Structure Using Fuzzy Logic

Abstract
The aim of this study is to evaluate vibrotactile perception via an e-textile structure on different parts of the body by different signal types and frequencies. First an e-textile structure was developed by the integration of a vibration motor to knitted fabric using conductive yarns. Then various signal waveforms at different frequencies were applied to diverse parts of the user's body via this novel textile structure. Signals were generated by using a DAQ (Data Acquisition) card. Finally vibrotactile perceptions were evaluated and compared by groups of people using fuzzy linguistic scales. It was found that the signal waveform and frequency had a significant effect on the vibrotactile perception. Furthermore the perception level of vibrotactile stimulation showed differences depending on the part of the human body. This e-textile based vibrotactile information could be highly valuable for applications like directional navigation, where the visual sense is restricted, for driving, for piloting and for medical applications like body relaxation against stress.

Key words: *vibrotactile perception, e-textiles, fuzzy logic, vibration motors, signal waveform, frequency, body parts.*

Introduction

Tactile sensations activate numerous mechanoreceptors in the outer layers of the skin. Tactile information is then transmitted directly to the brain from those mechanoreceptors to provide information about tactile sensations [1].

In a number of tactile displays developed, vibrotactile feedback stimulation is used to provide information about the direction or orientation of personal or vehicle movement [2 - 7], for deaf people to support speech vocalisation [8], for blind people to detect 3D patterns of an obstacle distribution [9, 10], to read printed material [11] etc.

Vibrotactile sensation is a kind of tactile sensation based on vibration motions. In vibrotactile sensations, the perception level depends on many factors connected with the characteristic of vibration stimuli, such as contact and friction values between the human skin and a sensed object, vibration frequency, magnitude, duration of vibration, type of vibration motions applied and the area of the contactor stimulating the skin [12 - 14].

The literature review mainly summarises the effect of vibration frequency ranging from 0.1 Hz to 1 KHz on the vibrotactile perception level. The effect was studied by different contactor measuring devices [15 - 19]. Some researchers reported that when the vibration frequency increases, the perception level increases [20 - 22], whereas others found that the perception level is independent of the vibration frequency [23, 24]. Indeed since the frequency working range is different in various studies, perception level results according to the frequencies used showed differences. Furthermore in most of the studies three regions of the body: the fingertip, forearm, and abdomen, are often used as a stimulated contact area.

Indeed the perception level of vibrotactile stimulation varies in different regions of the body, which may be explained by the innervation density of mechanoreceptors in the skin [25, 26]. For instance, the perception level in areas with high innervation densities, e.g. fingertips, is stronger than in those with low innervation densities, e.g. the arm [27]. In some of the studies, parts of the (i) upper body: abdomen, chest, shoulders, or head, (ii) lower body: feet and legs, buttocks, or back were subjected to vibration [28 - 30]. It was reported that low frequencies (from 0.5 to 1.25 Hz) caused discomfort in the upper body, whereas high frequencies (from 6.3 to 16.0 Hz) caused discomfort in the lower body [29].

Vibrations are not in the form of unitary stimuli. They are composed of a certain waveform, which can be regular or irregular [31]. Waveforms can also affect the level of vibrotactile perception. It was found in a modulated sinusoid waveform study, in which the amplitude of a base signal (e.g. 250 Hz) was modulated by a second sinusoid (e.g. 50 to 20 Hz), that the level of perception changed [32].

As seen from the factors mentioned above, during the design of a vibrotactile display there are many parameters which should be considered carefully. Furthermore during the design process, apart from factors affecting the perception level, devices that are used to stimulate the skin in wearable tactile communication systems must be lightweight, small and reliable.

In a few studies, the vibrotactile system is embedded on a textile structure. Cardin and Thalmann (2008) developed a vibrotactile jacket that can receive 3D directional information from a virtual environment [33]. In their system, flat DC vibration motors were used, connected by electrical wires embedded in soft tissue naps. Similarly Hao and Song (2010) designed a wearable vibrotactile display waist belt in order to get directional information of the target in an environment [34]. They used vibrating electric motors. In their system, tactile modules carrying the vibrating electric motor were fastened on a waist belt made of elastic braid. Additionally Barghout et al. (2009) and Rahal et al. (2009) conducted psychophysical experiments to investigate the continuous vibrotactile sensation on human skin with discrete vibration motors [35, 36]. In their studies, the vibration motors were attached to an arm band using Velcro. The arm band was wrapped around the forearm and electrical connections were made by using the electrical wires again. One more interesting study is the *Emotions Jacket* from *Philips®*. The Emotions Jacket is a tightly fitting garment which consists of a series of vibration motors sewn into the arms and torso. In response to what is

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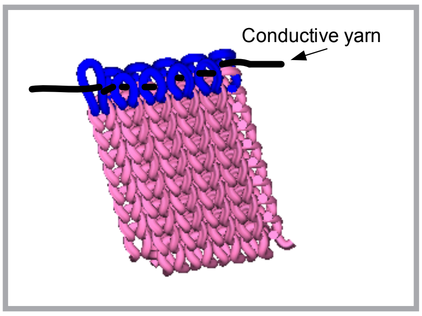

Figure 1. *3D representation of the 1 × 1 rib fabric.*

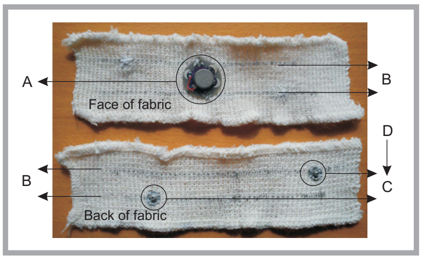

Figure 2. *Samples realised in our laboratory; A - wibration motor, B - transmission lines (conductive yarn paths), C - snap fasteners connection, D - voltage application point.*

happening on screen, these vibration motors are activated by a control unit. Thus certain feelings being experienced by the characters in the film can be perceived by the user [37].

According to the literature survey, in a few studies actuators used to provide vibrotactile sensations were tested by means of a textile structure. In those studies, it was noticed that actuators were only attached to textile structures and their electrical connections generally made using electrical wires. However, it would be interesting to integrate those actuators with a textile structure using conductive yarns instead of electrical wires.

Therefore, in view of the deficiency in the literature mentioned, we conducted a comprehensive study in order to analyse vibrotactile perception via an e-textile structure on different parts of the human body using different signal types and frequencies. As an actuator, a vibration motor was used, which was integrated with the textile structure by means of conductive yarns. In order to evaluate the perception level, fuzzy linguistic scales were used. Hence, the perception level was evaluated in terms of fuzzy relations and compared statistically.

In fact, our further aim was to develop an intelligent garment for visually impaired people that can enable to detect obstacles as well as guide the user among those obstacles. Vibration motions could be utilised with such a system as a guidance alert. Therefore, despite the deficiency in literature, before designing this type of smart clothing system, it was also important to know the influence of different signal waveforms and frequencies as well as different body local areas on the resulting vibrotactile perception. It is not easy to assess the equal subjective magnitude for all persons. However, the result of this study seems promising and could be essential for those who are also interested in designing wearable vibrotactile displays or vibrotactile smart clothing.

Experiments

Materials

In this study, a Arduino LilyPad Vibe Board® vibration motor was used as an actuator to ensure vibrotactile sensations due to its small dimensions (outer diameter: 20 mm, weight: 2 g), low power requirement (Max Applied Voltage: 5.5 V) and easy implementation.

To integrate the vibration motor with the textile structure as well as to form an electric circuit in the structure, silver plated nylon yarn with a linear resistance of <50 ohm/m and yarn count of 312/34f × 4 dtex was used. Silver plated nylon was chosen as conductive yarn because our previous experiments denoted that silver plated nylon yarns show the best compromise between signal quality and textile properties e.g. handle, stable and elastic, easy to weave, easy to integrate sensor etc. For the non-conductive area in the structure, 100% acrylic with a yarn count of 24 × 2 tex was used.

Formation of e-textile structure

To prevent short circuits, a knitted fabric sample was designed using the lay-in technique with a stitch density of 1×1 rib, where conductive yarns were hidden in

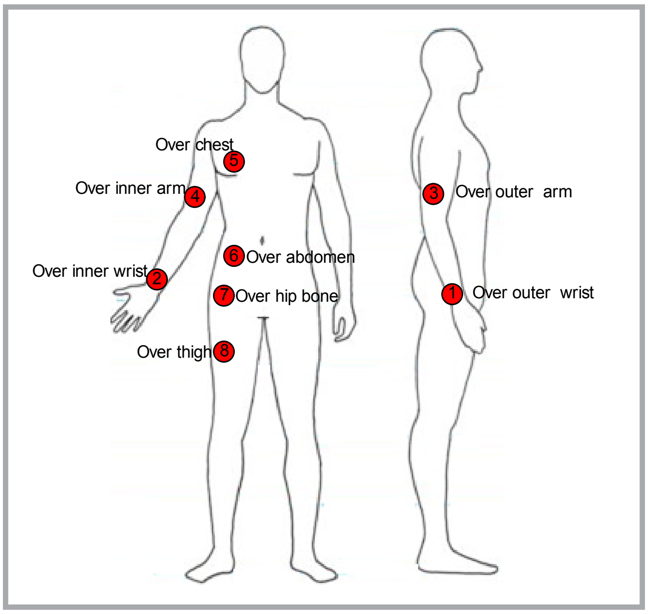

Figure 3. *Stimulated contact areas of human body during the measurements.*

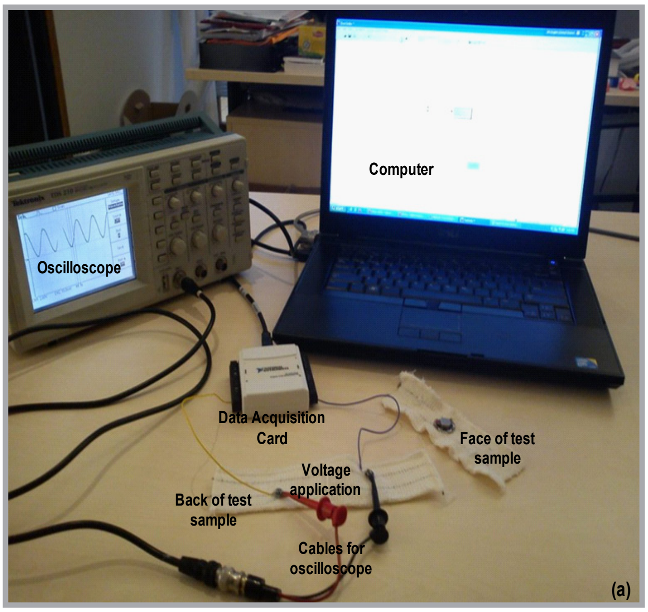

Figure 4. *Measurement-set up.*

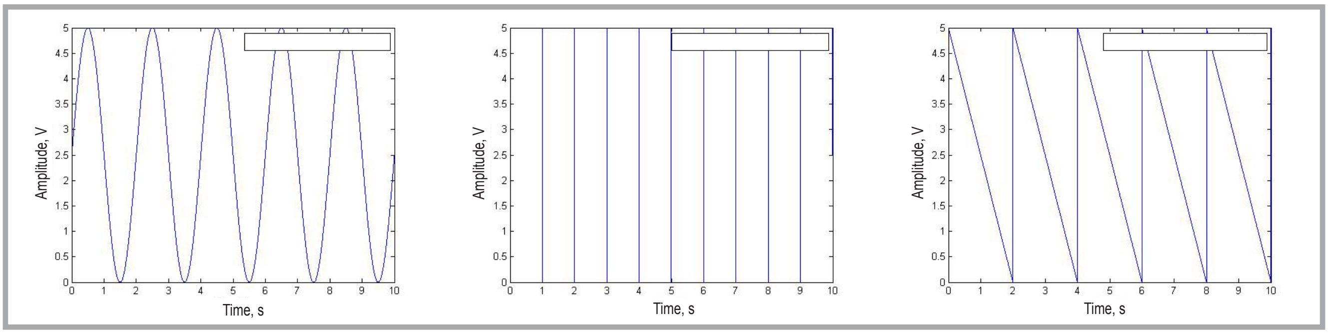

Figure 5. *Generated signals: sinwave, square wave, sawtooth wave with 5 V amplitude at 0.5 Hz.*

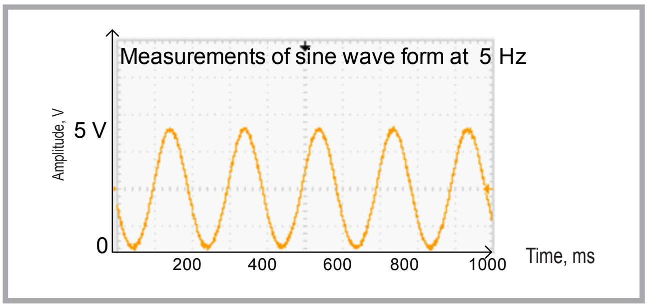

Figure 6. *Measured signal over the outer wrist during the sine wave form application with 5 V amplitude at 5 Hz.*

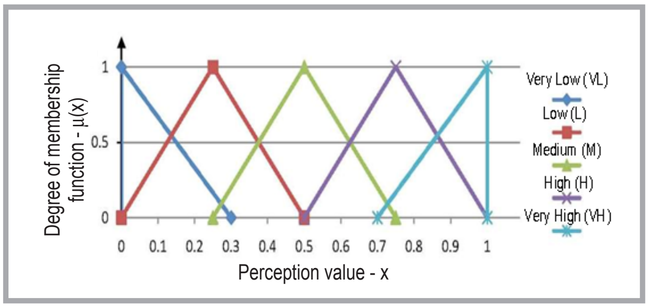

Figure 8. *Triangular fuzzy numbers for linguistic terms.*

the middle layer of the knitted fabrics, as seen in ***Figure 1***.

Knitted fabric samples were produced using a hand flat knitting machine. During the production of samples, to design an electrical circuit and connect vibration motors to a fabric, loops were formed among conductive yarns and then snap fasteners were sewn onto these loops. In this way the connection of the vibration motor to the textile structure was made using these loops. Afterwards signals passing through conductive yarns via snap fasteners were transmitted to the vibration motor. ***Figure 2*** shows the samples that were produced. The weight of samples were around 5.19 g with a length and width of 19 cm and 4 cm approximately.

Measurement set up

Experiments were conducted by applying three types of signal waveforms (square wave, sin wave, and saw tooth wave) at three different frequencies (0.5 Hz, 5 Hz and 50 Hz) to different part of the user's body, as seen in ***Figure 3***, with the samples mentioned above. Signals were generated in MATLAB using a National Instruments® DAQ (Data Acquisition) Card, and the frequency level was measured with an oscilloscope (see ***Figure 4***). The duration for each experiment was adjusted to 30 seconds [19]. The signals generated are shown in ***Figure 5*** for 0.5 Hz.

In order to analyse and compare the vibrotactile sensations perceived, samples were tested with three different wave forms at three different frequencies, on eight different body parts of the eight

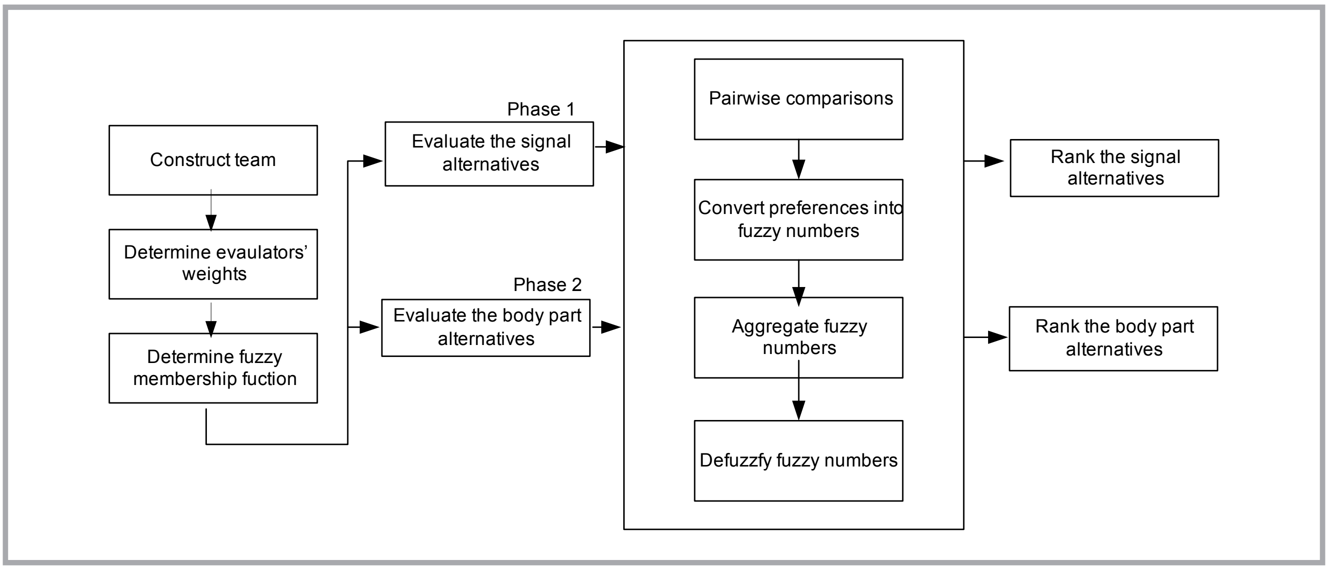

Figure 7. *Framework of the fuzzy evaluation method.*

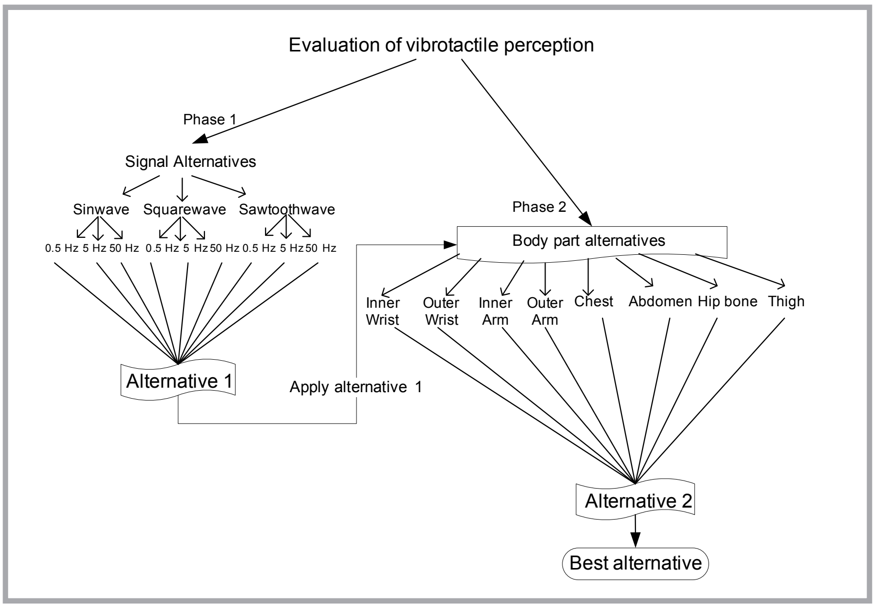

Figure 9. Hierarchy of the evaluation.

Table 1. Vibrotactile perception values of each evaluator according to signal alternatives.

	Sine wave			Square wave			Saw tooth wave		
	0.5 Hz	**5 Hz**	**50 Hz**	**0.5 Hz**	**5 Hz**	**50 Hz**	**0.5 Hz**	**5 Hz**	**50 Hz**
E1	VH	H	M	M	M	L	M	M	M
E2	H	M	M	H	M	M	H	H	M
E3	H	H	M	M	L	L	H	M	L
E4	VH	H	M	M	M	L	M	L	L
E5	VH	M	L	M	L	VL	M	M	L
E6	H	M	M	M	M	L	M	M	M
E7	H	M	M	M	M	L	H	M	L
E8	H	M	L	M	L	VL	H	M	M

people. E-textile structures were placed under a tightly fit garment composed of polyamide and elastane yarn in order to provide vibration sensations through the garment. This e-textile structure will be integrated into garments to form a smart clothing system in the further studies. For instance, the signal measured over the outer wrist when the sine wave form at 5 Hz was applied is shown in ***Figure 6*** (see page 93).

Evaluation method

Figure 7 (see page 93) explains the framework of the evaluation method according to fuzzy relations. As seen in figure, to construct a team, due to the known decreasing sensitivity of elderly humans, eight people (four men and four women) aged between 24 and 30 were selected for experiments [38]. Since all of the evaluators self-reported having a normal sense of touch, the weighting factor of each evaluator was considered equally:

Then the fuzzy membership function for vibrotactile perception was determined. The fuzzy data can be in linguistic terms, fuzzy sets or fuzzy numbers. The fuzzy scale is a set of fuzzy numbers $P_1,..., P_n$ defined in the interval $<A,B>$ and they are numbered according to their order to make a fuzzy decomposition:

$$\forall x \in < A, B >: \sum_{i=1}^{n} P_i(x) = 1 \qquad (1)$$

If the data are in linguistic terms instead of fuzzy numbers, then the fuzzy scale can be used due to fuzzy linguistic variables [39]. We used fuzzy linguistic terms according to the study of Kulak and Kahraman [40]. Hence the values of vibrotactile perception were expressed in the fuzzy linguistic scale, ranging from very low (VL) to very high (VH), as seen in ***Figure 8*** (see page 93). During the evaluation phase, a training session was first prepared to help the evaluators to become familiar with the linguistic terms of perception levels along body parts and situations. The training procedure can easily make the evaluator understand and unify the meaning of the evaluation terms, such as ‘very high’ and ‘medium’.

Then, since the fuzzy data are in linguistic terms, evaluations were transformed into standard fuzzy numbers, which were all assigned to crisp scores using ***Equation 2***, where the parameters {a, b, c} show the x coordinates of three corners of the triangular membership functions [41]. Afterwards evaluations for pairwise comparisons were aggregated using ***Equation 3*** [42].

$$triangle(x;a,b,c) = \begin{cases} 0, x < a \\ \dfrac{x-a}{b-a}, a \le x \le b \\ \dfrac{c-x}{c-b}, b \le x \le c \\ 0, c \le x \end{cases} \qquad (2)$$

$$\tilde{S}_i = \tilde{S}_{i1} \otimes w_{e1} \oplus \tilde{S}_{i2} \otimes w_{e2} \oplus ... \oplus \tilde{S}_{im} \otimes w_{em} \qquad (2.3)$$

where $\tilde{S}_i$ is the fuzzy aggregated score of the i^{th} case and w_{ei} is the weight of the i^{th} evaluator and $w_{ei} \in [0,1]$. $\otimes$ and $\oplus$ denote the fuzzy multiplication and fuzzy addition operators, respectively. Finally the best alternative having the highest perception level was selected. Results were also compared statistically. An ANOVA test was performed to compare the significance value of different alternatives (signal type and frequency, and body parts) and the perception level. In order to do the test, the SPSS® program was used and the statistical significance was set at $p < 0.05$.

Figure 9 shows the hierarchy of the evaluation phase. First the signal alternatives were evaluated, compared and ranked for the perception level. Secondly the best signal alternative applied on the e-textile structure was tested with different parts of the human body. Then the body part alternatives were evaluated, compared and ranked. Finally the best combination for the highest vibrotactile perception was selected.

Results

Results according to signal alternatives

Vibrotactile perception values of the eight evaluators according to signal alternatives are summarised in ***Table 1*** in fuzzy linguistic terms. In the table, the evaluators are denoted as E1, E2.., E8.

The perception values in fuzzy terms were transformed into fuzzy numbers

Table 2. *Aggregated fuzzy score of signal alternatives.*

Signal Type	Frequency	Aggregated fuzzy score
Sine wave	0.5 Hz	(0.57, 0.84, 1.00)
	5 Hz	(0.34, 0.59, 0.84)
	50 Hz	(0.18, 0.45, 0.68)
Square wave	0.5 Hz	(0.28, 0.53, 0.78)
	5 Hz	(0.15, 0.42, 0.65)
	50 Hz	(0.03, 0.25, 0.48)
Saw tooth wave	0.5 Hz	(0.37, 0.62, 0.87)
	5 Hz	(0.25, 0.50, 0.75)
	50 Hz	(0.12, 0.40, 0.62)

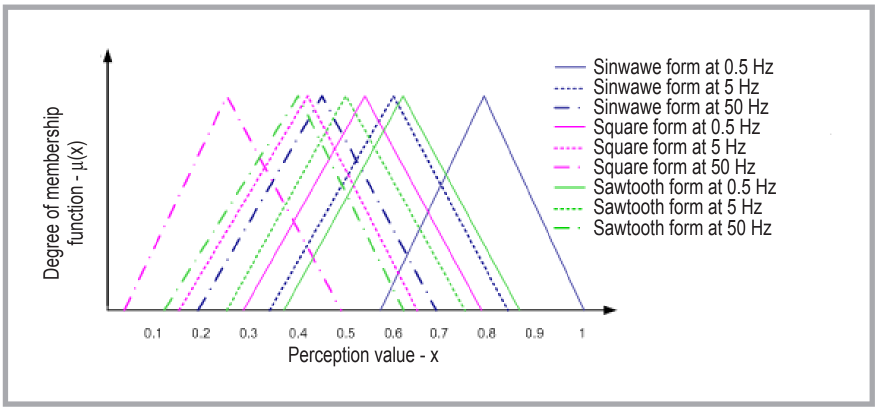

Figure 10. *Vibrotactile perception according to signal alternatives.*

using the linguistic scale shown in ***Figure 8***. Then they were aggregated as mentioned earlier. The aggregated fuzzy score of signal alternatives with their membership functions are shown in ***Table 2*** and ***Figure 10***, respectively.

Table 3. *Vibrotactile perception values of each evaluator according to body part alternatives.*

	Over							
	Outer wrist	**Inner wrist**	**Outer arm**	**Inner arm**	**Chest**	**Abdomen**	**Hip bone**	**Thigh**
E1	H	M	L	M	M	L	VH	VL
E2	VH	H	M	H	H	M	H	L
E3	H	M	M	H	H	M	VH	L
E4	VH	M	M	H	M	L	H	VL
E5	H	M	M	H	M	L	H	L
E6	VH	H	M	H	M	M	VH	VL
E7	H	M	M	M	M	L	H	L
E8	VH	H	M	H	M	L	VH	L

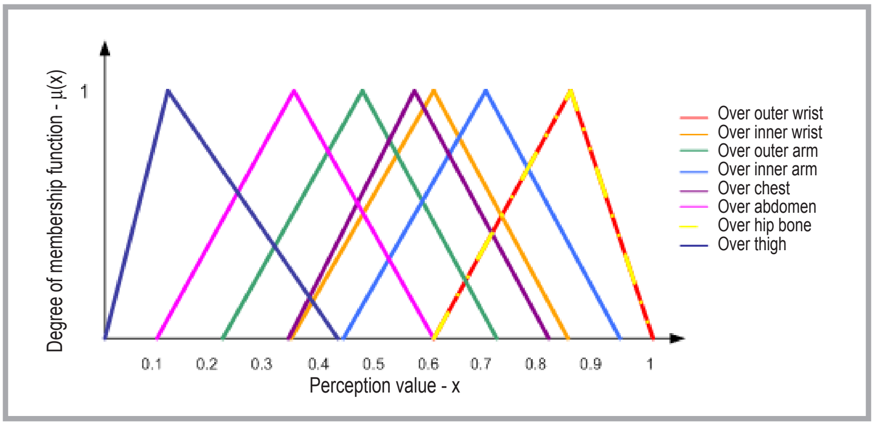

Figure 11. *Result of total evaluation of vibrotactile perception according to body parts.*

As can be noticed from ***Figure 10***, when the frequency of the signal increases, the perception level decreases. Moreover at the same frequencies the perception level of the square wave form is lower than that of both the saw tooth and sine wave forms. Furthermore sine wave forms at 0.5 Hz showed the highest vibrotactile perception level. The order of vibrotactile perception level of wave forms at the same frequencies is sine wave > saw tooth > square.

In addition to aggregated fuzzy scores, signal alternatives were also compared statistically. Based on ANOVA test results, the level of vibrotactile perception varied significantly with both signal type and frequency ($p < 0.001$; ANOVA).

These results can be explained by the structure of wave forms. In the sine wave form, an increase and decrease are seen uniformly. But in both the saw tooth wave and square waveforms, a sudden increase is seen, directly reflecting the vibration motion. In this way, it can be said that the tactile sensation is smooth in the sin wave form, whereas it is rough in both the saw tooth and square wave forms [43], which may affect the evaluator's perception negatively. Furthermore as the frequency increases, the continuity of vibration motion increases. However, at low frequencies the vibration motion is more discrete. From the results, it can be concluded that people prefer to feel discrete vibrations instead of continuous vibrations as an alert.

To sum up, in order to continue our experiments with different body part alternatives, the sine wave form at 0.5 Hz was chosen because it showed the highest vibrotactile perception among the signal alternatives.

Results according to body part alternatives

To compare the vibrotactile sensation perceived on various parts of the human body, a sample was used during the experiments in which a sine wave form signal at 0.5 Hz was applied on the different body parts of the evaluators.

The vibrotactile perception values of eight evaluators according to body part alternatives in fuzzy linguistic terms are summarised in ***Table 3***. Based on these results, the aggregated fuzzy score of body part alternatives with their membership functions is shown in ***Table 4*** and ***Figure 11***, respectively.

***Table 4.** Aggregated fuzzy score of body part alternatives.*

Body part alternatives	Aggregated fuzzy score
Outer wrist	(0.600, 0.875, 1.000)
Inner wrist	(0.344, 0.594, 0.844)
Outer arm	(0.219, 0.469, 0.719)
Inner arm	(0.438, 0.688, 0.938)
Chest	(0.313, 0.563, 0.813)
Abdomen	(0.094, 0.344, 0.594)
Hip bone	(0.600, 0.875, 0.100)
Thigh	(0.000, 0.156, 0.425)

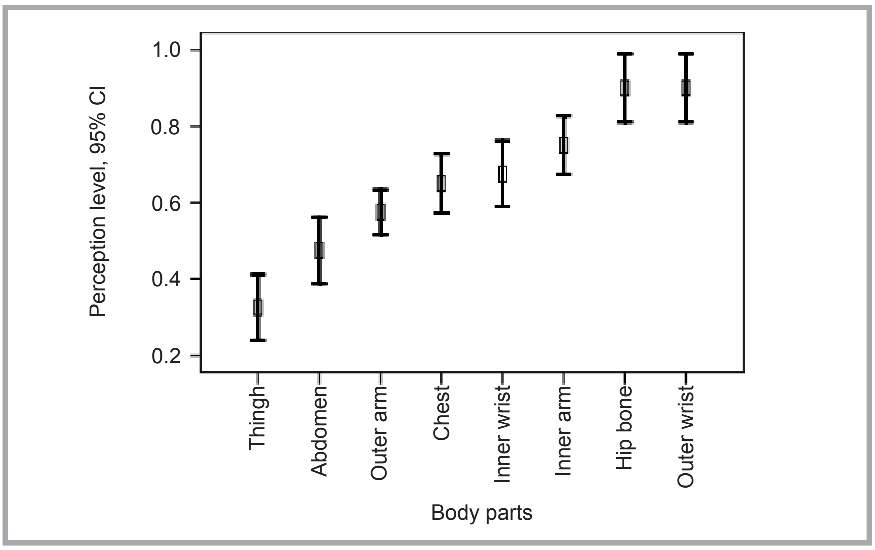

***Figure 12.** Result of total evaluation of vibrotactile perception according to body parts alternatives (95% Confidence Interval).*

Parallel to the aggregated fuzzy scores, the perception level at a 95% confidence interval is shown in ***Figure 12***. As seen in ***Figures 11*** and ***12***, the highest vibrotactile sensation was perceived over the outer wrist and hip bone area of the body of the evaluators, whereas the lowest was perceived over the thigh. The vibrotactile sensation perceived in rank from higher to lower on the body parts are over the outer wrist/over the hip bone, over the inner arm, over the inner wrist, over the chest, over the outer arm, over the abdomen, and the over thigh, respectively. Furthermore it was also found that the perception level over the outer wrist is higher than that over the inner wrist. On the contrary, the perception level over the outer arm is lower than that over the inner arm.

Moreover ANOVA test results also presented that the vibrotactile perception level significantly changes depending on the body part ($p < 0.001$; ANOVA). This could be attributed entirely to the distribution of sensory nerves on the human body, as mentioned in the literature. For instance, in a study on tactile displays, it was also reported that the vibratory threshold was higher in hips than in the abdomen and thigh, respectively, at 100 Hz [14]. Moreover in another study in which five people were exposed to a vertical sinusoidal wave force vibrating at various frequencies, it was reported that at 5 Hz the vibration is more sensible on the chest than on the abdomen and thigh [28].

Conclusion

In this study, the vibrotactile perception level was investigated in terms of fuzzy relations and then compared statistically. The influence of different signal wave forms (sine wave, square wave, and saw tooth wave) at different frequencies (0.5, 5 and 50 Hz) and on different body parts (wrist, arm, chest, abdomen, hip bone, thigh) on the resulting vibrotactile perception was evaluated by eight people (evaluators).

Results showed that the signal waveform and frequency had a significant effect on the vibrotactile perception level. It was found that as the frequency of the signal increases, the perception level decreases. Correspondingly it was deduced that people prefer to feel discrete vibrations instead continuous vibrations as an alert. According to our results, the order of the vibrotactile perception level of the wave forms at the same frequencies was sine wave > saw tooth > square. The highest vibrotactile perception level within the signal type alternatives was obtained with the sine wave form at 0.5 Hz.

Another result issuing from this study is that the perception level of the vibrotactile sensation showed differences due to the contact areas of the human body. The highest level of vibrotactile sensation was perceived over the outer wrist and hip bone area of the body of the evaluators, whereas the lowest was perceived over the thigh.

In summary, the e-textile based tactile information issuing from this study could be considered for applications like directional navigation, where the visual sense is restricted, such as a lack of a wide angle of view, overloaded drivers, cockpits etc. It could not only be highly valuable for driving, piloting or in aerial vehicles for alert purposes, but also beneficial for medical applications like body relaxation. We hope that these results could be essential for those who are interested in designing wearable vibrotactile displays or vibrotactile smart clothing as well.

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