Power requirements for vibrotactile piezo-electric and electromechanical transducers

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Abstract—*Human–machine information transfer through tactile excitation has addressed new applications in virtual reality, robotics, telesurgery, sensory substitution and rehabilitation for the handicapped in the past few years. Power consumption is an important factor in the design of vibrotactile displays, because it affects energy needs and the size, weight, heat dissipation and cost of the associated electronics. An experimental study is presented on the power required to reach tactile thresholds in electromechanical and piezo-electric transducers. Three different waveforms are considered, with an excitatory period formed by a burst of rectangular 50% duty cycle pulses (R50), rectangular low duty cycle pulses (RLO) and sinusoidal pulses (SIN). Ten different pulse repetition periods (RPs) were considered in the range 1/550–1/25 s. The voltage and current waveforms applied to the transducers at sensation thresholds in a group of 12 healthy subjects were sampled and stored in a digital oscilloscope. The average power was determined for each subject, and differences of two orders of magnitude were measured between the electromechanical and the piezo-electric transducer power consumption. Results show that, for the electromechanical transducer, a smaller power consumption of 25 μW was determined for RP = 1/25 s and the RLO waveform. In the case of the piezo-electric transducer, power of 0.21 μW was determined for SIN excitation and RP = 1/250 s. These results show the advantages of reducing power requirements for vibrotactile displays, which can be optimised by the choice of appropriate types of transducer, excitatory waveforms and pulse repetition periods.*

Keywords—*Power consumption, Vibrotactile excitation, Tactile displays, Tactile information transfer*

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1 Introduction

HUMAN–MACHINE information transfer through tactile excitation has addressed new applications in virtual reality, robotics, telesurgery, sensory substitution and rehabilitation for the handicapped in the past few years (ASAMURA *et al.*, 1998; HOWE *et al.*, 1995; IKEY *et al.*, 1997; ROSEN *et al.*, 1999). Tactile interfaces permit a distant transfer of pressure, force or texture sensation, allowing a human to perform remote control of devices with improved precision. More than three decades ago, the possibility of transferring visual information across the skin was demonstrated (BACH-Y-RITA *et al.*, 1969; COLLINS, 1970). Since then, understanding of the tactile sensory system and its interaction with tactile displays has improved significantly.

A haptic interface conveys a kinaesthetic sense of presence to a human operator interacting with a computer-generated environment (ADAMS and HANNAFORD, 1999). Pioneer work in the field of haptics produced a JPL force reflecting hand controller to develop tele-operator control paradigms (BEJCZY and SALISBURY, 1983). Also, a force-controllable articulated hand was used to explore sensing and control issues aimed at increasing robot dexterity (SALISBURY and CRAIG, 1982). Several strategies to improve time delay in force feedback were proposed to avoid instability in the control of the physical system. Compliance between the slave and environment and shared control between the operator and robot were used (KIM *et al.*, 1992).

The use of tactile feedback in telesurgery has been the subject of active research as a means to improve the remote control of surgical instruments (GREEN *et al.*, 1995; TAYLOR *et al.*, 1995). Telesurgery aims to minimise the impact of surgery on the patient, involving small incisions (1–2 cm) that reduce tissue trauma, pain and recovery time (ROSEN *et al.*, 1999). Several papers indicate the importance of tactile feedback to the surgeon to determine the exact location of tumours in tissue (DARGAHI, 2000; NORTON *et al.*, 1990; ROSEN *et al.*, 1999; SCOTT and DARZI, 1997). A basic form of telesurgery is endoscopic surgery, and the possibility of adding tactile feedback

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from the instruments to the surgeon has been explored recently (TAYLOR, 1995). Endoscopic instruments should allow the surgeon the required degrees of freedom for movement, tactile feedback and appropriate visualisation (BUESS *et al.*, 2000).

Novel, minimally invasive surgical techniques, such as laparoscopy and thoracoscopy, have separated the hands of the surgeon from the surgical site (HOWE *et al.*, 1995). In those situations, the surgeon's perception is limited to visual feedback from a video camera, or gross motion and force feedback through the handles of long instruments. The need to develop new technologies to overcome this sensory deficit has been recognised (ROSEN *et al.*, 1999). It was shown that the experimental use of a manipulator with tactile feedback yielded better results than a standard endoscopic instrument (ROSEN *et al.*, 1999). Another prototype with tactile feedback for head and neck surgery has been used experimentally (BUESS *et al.*, 2000; BURCKHARDT *et al.*, 1995).

In robotics and virtual reality (ELLIS, 1994), haptic interfaces are being developed to provide the human with enough information to manipulate a remote or virtual environment (CHU *et al.*, 1997; DIONISIO *et al.*, 1997; IKEY *et al.*, 1997; COLWELL *et al.*, 2000; WALAIRACHT *et al.*, 2000; ASAMURA *et al.*, 1998). In virtual reality, there is a need for physical interaction between the user and the computer to enhance the feeling of reality of the synthetic space in which the user is immersed. Haptic sensation has been proposed to complement visual image displays and auditory displays (IKEY *et al.*, 1997; ASAMURA *et al.*, 1998). Gloves have been developed to allow human interaction with virtual environments created by a computer (MACPHERSON and KEPPELL, 1998). When the subject explores the surface of the virtual object, tactile displays apply forces on the hand or fingers (WALAIRACHT *et al.*, 2000). Also, an application to identify textures was developed using tactile feedback (ASAMURA *et al.*, 1998). Using cameras, visual information was transformed into tactile information and applied to the distal portion of the finger to simulate virtual touch on objects (OWAKI *et al.*, 1999).

Industrial applications for tele-operation using tactile feedback have been proposed as well (BICCHI *et al.*, 2000). Other applications of tactile feedback to provide additional information to the user have been proposed for aircraft pilots and divers. A device to avoid the loss of spatial orientation of aircraft pilots when visual clues are unavailable was developed at the Naval Aerospace Medical Research Laboratory, Pensacola, Florida, USA. It consists of an array of tactile transducers mounted on a lycra shirt to provide information about the direction of gravity (RUPERT, 2000).

Tactile interfaces, including vibrotactile and electrotactile excitation, have been used extensively as an aid for the blind and deaf community (BACH-Y-RITA *et al.*, 1969; FRIKSEN-GIBSON *et al.*, 1987; MILETIC, 1994; ZIMMERMAN, 1990). One classical example is the optical to tactile converter (Optacon), where vibrating pins represent the intensity pattern as a camera is manually scanned across a printed page (LINVILL and BLISS, 1966). In the Optacon design, the average power required to reach sensation threshold was estimated based on a model of the skin with mechanical load. Sinusoidal excitation with a period of 1/200 s and displacement of 10 μm for the transducers was employed. The average power consumption per transducer was estimated at 27 μW with a piezo-electric transducer (LINVILL and BLISS, 1966). Also, the need for reducing size, weight and power consumption to allow portability of sensory aids has been recognised (KACZMAREK *et al.*, 1991; BRABYN, 1985; CHOLEWIAK and CRAIG, 1981; NUNZIATA *et al.*, 1989; PEREZ and MUÑOZ, 1995; PEREZ *et al.*, 2000).

The human tactile system frequency response was measured using sinusoidal excitation, and the maximum sensitivity was determined to be around the repetition period (RP) of 1/250 s (VERILLO *et al.*, 1969; JOHNSON and PHILLIPS, 1981; LAMORE and KEEMINK, 1988; SUMMERS *et al.*, 1994; GESCHEIDER *et al.*, 1990). Based on this result, some tactile interfaces use sinusoidal excitation around RP = 1/250 s (LINVILL and BLISS, 1966). Other tactile interfaces use rectangular pulses with RP = 1/150 s (RUPERT, 2000). The duty cycle (DCY) measured as a percentage of a rectangular waveform is DCY = 100 PW/RP, where PW is the pulse width. Using electromechanical transducers, it was shown that tactile excitation with rectangular pulses has some advantages over sinusoidal excitation (PEREZ and MUÑOZ, 1995). The DCY of a rectangular pulse waveform can be controlled to be low, and therefore the power in the waveform can be reduced relative to a 50% DCY waveform. Additionally, because of the short PW, low DCY waveforms can be multiplexed and share hardware to reduce further the electronics, size and power consumption. Another possible advantage of using rectangular instead of sinusoidal waveforms is that the electronics required to generate the rectangular waveform are simpler (PEREZ *et al.*, 2000). For example, a rectangular pulse can be generated using a single transistor operating as a switch in cutoff and saturation regions.

Two- or three-dimensional spatial information associated with objects can be passed through the tactile sense using arrays of transducers. This is the case in aids for the handicapped and in virtual reality, where spatial form, edges and texture can be important components of the information transferred through the skin (ASAMURA *et al.*, 1998). A problem common to all tactile arrays is power consumption, as they are composed of several dozen transducers (CHOLEWIAK and WOLLOWITZ, 1992; SAUNDERS, 1983). Therefore there is an advantage in suitable selection of the transducer type and the excitatory waveform parameters.

The power requirement is an important factor in the design of vibrotactile displays. In general, higher power consumption in man–machine interfaces leads to larger and more expensive electronics to drive the interface, heavier instrumentation and a larger battery supply for portable devices and produces increased heat dissipation. A tactile interface with reduced power requirements to reach sensation thresholds has been recognised as an important factor in the design of portable devices to aid visually handicapped or deaf individuals (CHOLEWIAK and WOLLOWITZ, 1992; NUNZIATA *et al.*, 1989; SUMMERS *et al.*, 1994).

The appropriate specification of the parameters of the excitatory waveform, matching them to the tactile system characteristics, allows reduction of the tactile display power requirements and, hence, the hardware components (SAUNDERS, 1983; VAN DOREN, 1987; KACZMAREK *et al.*, 1985). Several theoretical studies have been presented partially achieving this goal in vibrotactile stimulation (NUNZIATA *et al.*, 1989; PEREZ and WEED, 1991; PEREZ, 1991; PEREZ *et al.*, 2000; KACZMAREK *et al.*, 1985; KACZMAREK *et al.*, 1991; SAUNDERS, 1983) and in electrotactile stimulation (SZETO and SAUNDERS, 1982; KACZMAREK *et al.*, 1991; 1992).

The PW for a driving waveform, composed of a train of rectangular pulses followed by a recovery time, was optimised so as to maximise the ratio between the power delivered to the frequency region of maximum tactile sensitivity (25–700 Hz) and the total power delivered by the waveform. Optimum PWs were in the range 0.7–1.2 ms (PEREZ and MUÑOZ, 1995). It was shown in NUNZIATA *et al.*, (1989) and PEREZ and WEED (1991) that the low DCY pulses reach similar sensitivity to the 50% DCY pulses while reducing the power delivered by the waveform. However, the power reduction was theoretically estimated based on the energy of the waveform without actual measurements. In the reviewed literature, no experimental results were found determining the power consumption in tactile interfaces as is proposed in the present paper.

2 Methods

2.1 *Overview of the experiment*

The present study determined experimentally the power required to reach the tactile thresholds using electromechanical and piezo-electric transducers. Three different types of excitatory waveform were compared: rectangular 50% DCY (R50), rectangular low duty cycle with a fixed PW = 0.7 ms (RLO) and sinusoidal (SIN) waveform, for ten different repetition periods in the 1/550–1/25 s range. Preliminary results for a piezo-electric transducer were presented in Perez *et al.* (2002). For each of the ten repetition periods and using the three different waveforms, R50, RLO and SIN, the voltage and current waveforms at sensation threshold were measured. These measurements were performed for the electromechanical and the piezo-electric transducers.

2.2 *Population and measured parameters*

For this purpose, the sensation thresholds were measured on 12 young, healthy subjects (21–27 years old) using the methods of the limits (Coren and Ward, 1989). The sensation threshold was defined as the minimum energy required for a stimulus to be perceived by a subject (Coren and Ward, 1989). The thresholds were determined for each of the three waveforms for ten different RP values: 1/550, 1/450, 1/350, 1/300, 1/250, 1/200, 1/150, 1/100, 1/50 and 1/25 s. The voltage and current waveforms applied to the transducer while the subject reached threshold were stored in a digital oscilloscope for later computation of power consumption.

2.3 *Experimental procedure*

The experiments considered three different excitatory waveforms, each one composed of a fixed stimulatory period of 200 ms followed by a recovery time of 1 s, the latter to prevent adaptation of the tactile system (Perez *et al.*, 2000). In each type of waveform, the stimulatory period was formed by a train of rectangular pulses (R50, RLO) or sinusoidal pulses (SIN). All waveforms were preprogrammed on a system based on the microcontroller Intel 80196, connected through a serial port to a personal computer, and therefore the time involved in changing from one type of stimulus to another was not significant (Perez *et al.*, 2000). The three waveforms and the parameters have been used in previous studies to estimate power consumption theoretically (Nunziata *et al.*, 1989; Perez and Weed, 1991; Perez and Muñoz, 1995) and to determine two-point spatial resolution (PEREZ *et al.*, 2000).

The power required by the transducer to excite the tactile system at threshold levels was measured. The voltage applied to the transducer and measured in volts at sensation threshold was determined experimentally for each subject. The thresholds were expressed in the waveform amplitudes, in volts peak-to-peak, applied to the transducers. The index finger was selected for these experiments, because it has been used in assistive devices (Cholewiak and Craig, 1984) and is the principal area used for tactile exploration (Van Doren *et al.*, 1987; Coren and Ward, 1989; Summers *et al.*, 1994; Perez *et al.*, 2000) because of its high spatial resolution. One day prior to the test, all individuals were familiarised with the threshold measurement method, in two 30 min sessions.

2.4 *Experimental system*

Two types of transducer were employed, an electromechanical and a piezo-electric transducer. The electromechanical

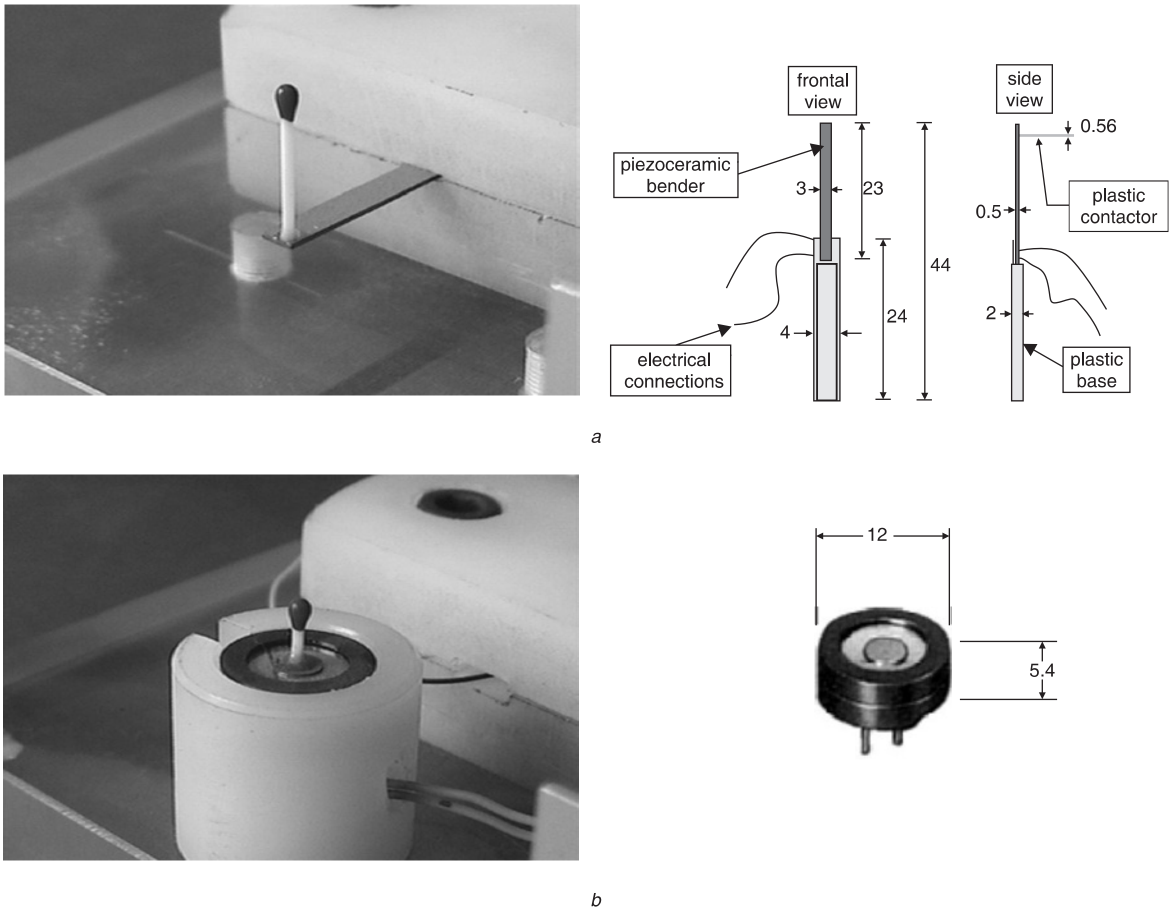

Fig. 1 *(a) Piezo-electric and (b) electromechanical transducer*

transducer[*] was used in NUNZIATA *et al.* (1989) and PEREZ and MUÑOZ (1995). This transducer has a cylindrical shape and is 12 mm in diameter and 5.4 mm tall. The piezo-electric transducer is a bimorph rectangular bender,[†] of 23 mm length, 3 mm width and 0.5 mm thickness, used in PEREZ *et al.* (2000; 2002). It was mounted in a cantilever manner, with 166 mm out of the plastic base and free to oscillate. Both types of transducer were mounted as shown in Figs. 1*a* and *b*.

The experiments were performed on the distal part of the index finger using a circular contactor of 1.5 mm diameter with no surround. The fingers rested on an acrylic cover with a circular perforation of 3.5 mm diameter, to allow the contactor to touch the skin. This particular arrangement is similar to several experimental tactile displays, including the Optacon (SUMMERS *et al.*, 1994; RADWIN *et al.*, 1993; MUIJSER, 1994; PEREZ *et al.*, 2000).

The resonant frequency for the electromechanical transducer was measured using a Fotonic Sensor[‡] at 1700 Hz. The resonant frequency for the piezo-electric transducer was also measured at 680 Hz. The piezo-electric transducer showed a relatively flat response up to 550 Hz. The resonant frequencies, intrinsic properties of both transducers, were out of the excitatory waveform fundamental components (25–550 Hz). In principle, more efficiency could be obtained by building transducers with resonant frequencies closer to the region of highest tactile sensitivity.

2.5 *Measured variables and post-processing analysis*

The instantaneous power required by the transducer to reach the sensation threshold in each subject was determined by measuring the current and voltage waveforms applied to the transducer using the circuit shown in Fig. 2. The current through the transducer was determined by Ohm's law $i = v_2/R$, and the voltage across the transducer was $(v_1 - v_2)$. R is a small resistor in series with the transducer used to measure v_2 with an oscilloscope. The series resistor was added to be able to measure the current across the transducer by determining the voltage drop on the resistor $i = v/R$. The resistor had to be small, but had to allow the voltage drop across it to be measured. If R was too small, the voltage drop would be negligible. Measurements of the voltage drop across the transducer were performed with and without the resistor R, with only negligible differences in the waveform shape being found. The shape of the voltage pulse depended on the impedance of the transducer and the power supply.

The voltage and current waveforms applied to the transducers to reach sensation thresholds were sampled and stored in a digital oscilloscope[**] using two channels. These waveforms were then transferred to a personal computer so that the average power P_{AV} could be computed, with the following calculation being implemented in Matlab:

$$v[k] = (v_1[k] - v_2[k]) \tag{1}$$

$$i[k] = \frac{v_2[k]}{R} \tag{2}$$

$$p[k] = v[k] \times i[k] \tag{3}$$

where $p(k)$ is the instantaneous power for one RP, and $v(k)$ and $i(k)$ are the kth samples from the voltage and current waveforms through the transducer. The average power is computed as

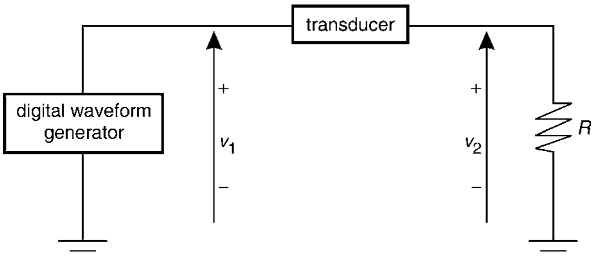

Fig. 2 *Circuit employed to measure voltage and current through transducer*

$$P_{AV} = \frac{1}{N}\sum_{k=0}^{N-1} v[k] \times i[k] \tag{4}$$

where N is the total number of samples within one RP ($N = 4096$ is the maximum number of samples captured by the digital oscilloscope).

Statistical analysis of the experimental data was performed to determine the significance of the different average power results for different test conditions. ANOVA was applied to determine if there were statistically significant differences among the three main variables considered in the experiments: transducers, excitatory waveforms and RP values. Furthermore, the Tukey test was applied to determine which specific pairs were significantly different (ROSNER, 1986).

3 Results

3.1 *Sensation thresholds*

Tables 1 and 2 show the average sensation thresholds and the standard deviation for the 12 subjects for RPs in the range 1/550–1/25 s, for the electromechanical and piezo-electric transducers, respectively. Both Tables present results for the three excitatory waveforms, R50, RLO and SIN. The thresholds are expressed in the waveform amplitudes in volts peak-to-peak applied to the transducers.

The force F, in newtons, is related to the applied voltage V in a piezoceramic bimorph (PZT5A) mounted in cantilever manner by $F = 10.43\,(ta)/LV$, where L is the length, a is the width, and t is the thickness. Therefore the force thresholds were estimated using this relationship, with the average voltage measured on the transducer for each RP. The results are shown in Table 3 and expressed in millinewtons.

Table 1 Sensation thresholds for electromechanical transducer, shown as average voltage ±1 standard deviation

	Waveform		
RP, s	RLO, V	R50, V	SIN, V
1/550	0.32 ± 0.12	0.26 ± 0.10	0.52 ± 0.23
1/450	0.26 ± 0.09	0.23 ± 0.08	0.48 ± 0.22
1/350	0.24 ± 0.09	0.21 ± 0.09	0.40 ± 0.19
1/300	0.22 ± 0.09	0.19 ± 0.08	0.36 ± 0.15
1/250	0.19 ± 0.08	0.17 ± 0.07	0.31 ± 0.11
1/200	0.22 ± 0.07	0.20 ± 0.07	0.29 ± 0.10
1/150	0.25 ± 0.10	0.23 ± 0.07	0.36 ± 0.19
1/100	0.25 ± 0.09	0.24 ± 0.07	0.63 ± 0.20
1/50	0.29 ± 0.11	0.26 ± 0.09	1.08 ± 0.33
1/25	0.34 ± 0.11	0.30 ± 0.08	1.33 ± 0.28

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[*] Model QMB-105, Star Micronics

[†] Morgan Matroc

[‡] MTI Instruments

[**] Voltcraft PCS64i

Table 2 Sensation thresholds for piezo-electric transducer, shown as average voltage ±1 standard deviation

RP, s	Waveform RLO, V	 R50, V	 SIN, V
1/550	1.88 ± 0.59	2.53 ± 0.92	2.13 ± 0.87
1/450	2.08 ± 0.59	2.47 ± 1.04	2.19 ± 1.02
1/350	1.82 ± 0.47	2.34 ± 0.91	2.04 ± 0.97
1/300	1.79 ± 0.57	2.14 ± 0.86	1.90 ± 0.79
1/250	1.75 ± 0.67	1.93 ± 0.81	1.76 ± 0.60
1/200	1.83 ± 0.54	2.24 ± 0.93	2.40 ± 1.07
1/150	1.92 ± 0.53	2.55 ± 1.06	3.72 ± 1.72
1/100	1.99 ± 0.48	2.64 ± 1.08	6.34 ± 1.91
1/50	2.26 ± 0.48	3.01 ± 1.13	9.65 ± 2.72
1/25	2.49 ± 0.61	3.70 ± 1.20	12.89 ± 3.58

3.2 *Average power consumption*

Fig. 3 shows an example of the instantaneous voltage and current waveforms that were acquired by the digital oscilloscope and the instantaneous power computed for the electromechanical (Fig. 3*a*) and piezo-electric (Fig. 3*b*) transducer. In Fig. 3*a*, the RLO voltage, current and power waveforms are shown for one period as a function of time for RP = 1/100 s and PW = 0.7 ms. Fig. 3*b* shows the R50 voltage current and power waveforms for one period as a function of time for RP = 1/100 s and 50% DCY. Using (4), the instantaneous power waveforms were employed to compute P_{AV} required for the transducers to reach sensation thresholds for each RP, for each of the three types of waveform and for the two types of transducer. Based on these measurements, the average power consumption, ±1 standard deviation, for the 12 subjects was determined for each RP.

Figs 4*a* and *b* show, in log scale, the average power consumption at sensation threshold for the 12 subjects as a function of the RP for both types of transducer (electromechanical and piezo-electric) and for the three types of waveform (R50, RLO and SIN). In Fig. 4*a*, we can observe that the average power consumption for the electromechanical transducer was almost two orders of magnitude larger than that of the piezo-electric transducer. In the case of the electromechanical transducer, the minimum power consumption was 25 μW and occurred at RP = 1/25 s for the RLO waveform. In the case of the piezo-electric transducer, the minimum power consumption was 0.21 μW and occurred at RP = 1/250 s, for the SIN waveform. The maximum sensitivity of the tactile system was around 250 Hz, as can be observed in Fig. 4*a* for the sinusoidal excitation (Verillo *et al.*, 1969). In the case of the rectangular waveforms (RLO and R50), the harmonics of the fundamental pulse repetition period were present, and therefore the maximum sensitivity could be reached at longer RPs (Perez and Muñoz, 1995).

Table 3 Force thresholds estimated for piezo-electric transducer based on force–voltage relationship provided by manufacturer. Estimation was computed for average threshold voltage applied to transducer on group of 12 subjects

RP, s	Waveform RLO, mN	 R50, mN	 SIN, mN
1/550	2.4	3.6	12.6
1/450	2.2	2.9	9.5
1/350	2.0	2.5	6.5
1/300	1.9	2.5	3.6
1/250	1.8	2.2	2.3
1/200	1.7	1.9	1.8
1/150	1.8	2.2	1.9
1/100	1.8	2.3	2.0
1/50	2.1	2.4	2.2
1/25	1.9	2.4	2.1

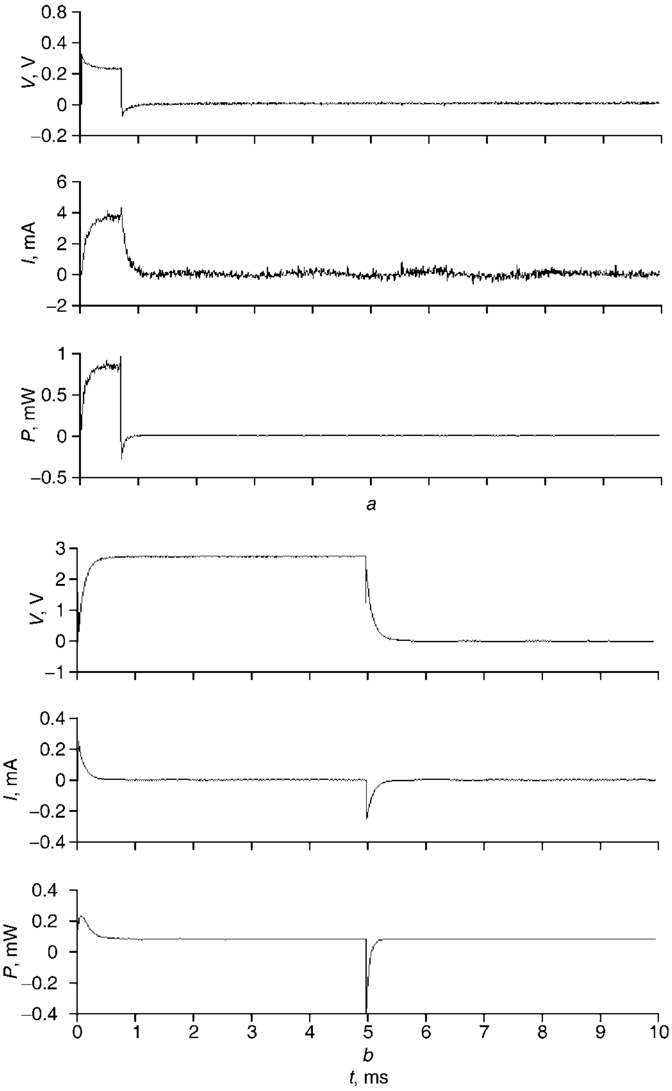

Fig. 3 *Instantaneous voltage, current and power waveforms as function of time for one RP. (a) Electromechanical transducer with RLO and (b) piezo-electric transducer with R50*

For the electromechanical transducer, it can be observed in Figs 4*a* and *b* that the power consumption decreased as a function of the RP for RLO, R50 and SIN in the range 1/550–1/250 s. However, in the range 1/200–1/25 s, the power consumption increased as a function of RP for R50 and SIN and decreased for RLO. The inverse relationship between power consumption and RP for RLO can be explained by observing the current waveform in Fig. 3*a*, where there is current flow during the whole duration of the voltage pulse. Therefore the power consumption decreased with the PW as RP increased. For the R50 waveform, the PW increased with DCY, and therefore the power consumption also increased. For the RLO, the PW was fixed at 0.7 ms, and therefore power consumption did not increase with RP. In contrast to the electromechanical transducer, the current flow in the piezo-electric transducer dropped to zero before the voltage pulse, as shown in Fig. 3*b*, and therefore the power was not proportional to the PW. The power consumption of both types of transducer differed by two orders of magnitude.

Results of the ANOVA applied to the experimental data for transducers, excitatory waveforms and RP values follow.

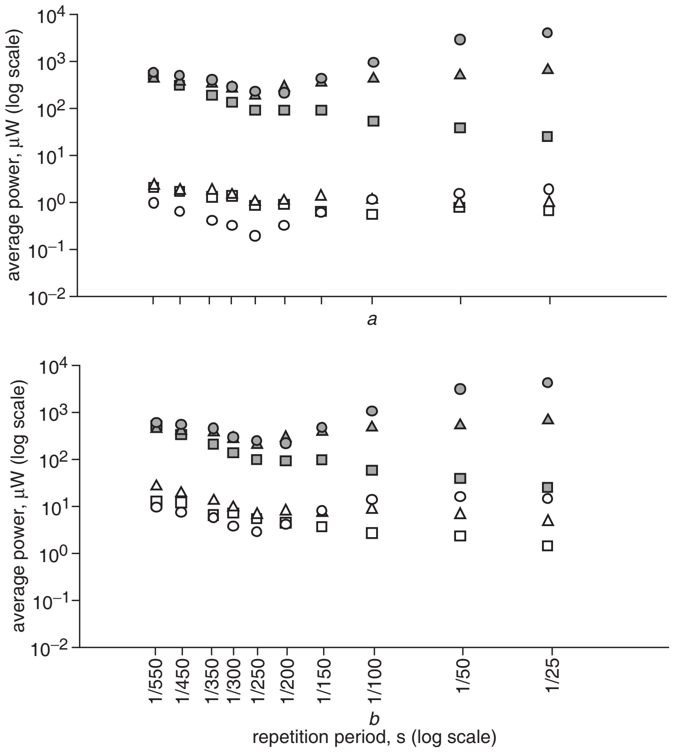

Fig. 4 *(a) Average power required to reach tactile thresholds as function of RP (in log scale) considering positive and negative power. (b) Average power required to reach tactile thresholds as function of RP (in log scale) considering only positive power. (▲) Electromechanical–R50; (■) electromechanical–RLO; (●) electromechanical–SIN; (△) piezo-electric–R50; (□) piezo-electric–RLO; (○) piezo-electric–SIN*

Also, results of the Tukey test applied to specific pairs are presented.

(i) Transducers: ANOVA compared mean power consumption between the transducers for the three different waveforms. It was found that all means were significantly different for the three waveforms, RLO, R50 and SIN. For RLO, $p < 0.001$, the factor F varied in the range 14.8–47.2, and the degrees of freedom were 23. For R50, $p < 0.001$, the factor F varied between 15.1 and 27.7, and the degrees of freedom were 23. For SIN, $p < 0.05$, the factor F varied within 7.1–81.2, and the degrees of freedom were 23.

(ii) Excitatory waveform: ANOVA was applied to compare the power consumption of different waveforms, RLO, R50 and SIN, for each transducer and each RP. For the electromechanical transducer, it was found that there were significant differences for RP $\geq 1/250$ with $p < 0.05$, the factor F varied in the range 3.3–64.2, and the degrees of freedom were 35. For RP $< 1/250$, no significant differences were found. The Tukey test showed that differences were significant ($p < 0.05$) among the following waveform pairs for different RP values. For RP $= 1/25$: between R50 and SIN and between RLO and SIN. For RP $= 1/50$: between R50 and SIN and between RLO and SIN. For RP $= 1/100$: between R50 and RLO, R50 and SIN and RLO and SIN. For RP $= 1/150$: between R50 and RLO. For RP $= 1/200$: between R50 and RLO. For RP $= 1/250$: between R50 and RLO. For the piezo-electric transducer, it was also found that there were significant differences ($p < 0.05$) in power consumption for different waveforms at all different RP values, the factor F varied in the range 3.3–9.7, and the degrees of freedom were 35. The Tukey test showed that differences were significant ($p < 0.05$) among the following waveform pairs for different RP values. For RP $= 1/25$: between RLO and SIN. For RP $= 1/50$: between RLO and SIN. For RP $= 1/100$: between R50 and RLO. For RP $= 1/150$: between R50 and RLO and between R50 and SIN. For RP $= 1/200$: between R50 and SIN and between RLO and SIN. For RP $= 1/250$: between R50 and SIN and between RLO and SIN. For RP $= 1/300$: between R50 and SIN and between RLO and SIN. For RP $= 1/350$: between R50 and SIN and between RLO and SIN. For RP $= 1/450$: between R50 and SIN and between RLO and SIN. For RP $= 1/450$: between R50 and SIN and between RLO and SIN.

(iii) RP values: ANOVA was applied to the power consumption for different RP values (1/25–1/550) for each transducer and each waveform. In all six cases (electromechanical transducer with RLO, R50 and SIN, and the piezo-electric transducer with RLO, R50 and SIN) differences in power consumption as a function of RP value were statistically significant ($p < 0.01$). The factor F varied in the range 2.9–28.9, and the degrees of freedom were 119 in all six cases. The Tukey test showed that only certain pairs were significantly different ($p < 0.05$) as follows: electromechanical R50 (pairs 1/25 with RPs in the range 1/350–1/200); RLO (pairs 1/550 with RPs in the range 1/25–1/450, pairs 1/450 with RPs in the range 1/25–1/50); SIN (pairs 1/25 with RPs in the range 1/550–1/100, pairs 1/50 with RPs in the range 1/550–1/100). Piezo-electric: R50 (pairs 1/550 with RPs in the ranges 1/50–1/25 and 1/250–1/200); RLO (pairs 1/300 with RPs 1/100 and 1/25, 1/450 with RPs in the range 1/250–1/25, 1/550 with RPs in the range 1/250–1/25); SIN: (pairs 1/25 with RPs in the range 1/450–1/150, 1/50 with RPs in the range 1/350–1/150, 1/100 with 1/250).

The piezo-electric transducer had a capacitive behaviour, as shown in Fig. 3*b*. A positive current went through the transducer during the rise time of the rectangular pulse and a negative one went through during the fall time. The negative current resulted in a negative power that the device delivered to the power source. In the case of an ideal capacitor, operating in sinusoidal steady state, this negative power is exchanged back and forth between the source and the capacitor without any power loss. In the case of the piezo-electric transducer, the negative power may not be passed back entirely by the source to excite the transducer in the next cycle. Therefore two different sets of data are provided for this transducer that consider the two possible extreme conditions, where the negative power is not lost (Fig. 4*a*) and where the negative power is completely lost (Fig. 4*b*). Statistical analysis was performed on the data where the negative power was lost completely (Fig. 4*b*) to study the three main variables considered in the experiments: transducers, excitatory waveforms and RP values.

(i) Transducers: ANOVA showed that differences in power consumption between the piezo-electric and electromechanical transducer were statistically significant. In this case, all means between the two transducers were significantly different for the three different waveforms. For RLO, $p < 0.005$, the factor F was in the range 14.0–24.1, and the degrees of freedom were 23. For R50, $p < 0.005$, the factor F was in the range 13.8–46.7, and the degrees of freedom were 23. For SIN, $p < 0.05$, the factor F was in the range 6.8–80.7, and the degrees of freedom were 23.

(ii) Excitatory waveforms: ANOVA was applied to compare power consumption among the three different waveforms RLO, R50 and SIN for the piezo-electric transducer. It was found that there were significant differences ($p < 0.05$) in power consumption for different waveforms at the following RP values: 1/25, 1/50, 1/100, 1/250, 1/300, 1/350, 1/450 and 1/550. The Tukey test showed that differences were significant ($p < 0.05$) among the following waveform pairs for different RPs: For RP = 1/25: between RLO and SIN and between R50 and SIN. For RP = 1/50: between RLO and SIN and between R50 and SIN. For RP = 1/100: between RLO and R50 and between RLO and SIN. For RP = 1/250: between SIN and R50. For RP = 1/300: between SIN and R50. For RP = 1/350: between SIN and R50. For RP = 1/450: between SIN and R50. For RP = 1/550: between SIN and R50.

(iii) RP values: ANOVA was applied to the power consumption for different RP values (1/25–1/550) for each waveform in the piezo-electric transducer. In the three cases (RLO, R50 and SIN), differences in power consumption as a function of RP value were statistically significant ($p < 0.01$). The Tukey test showed that only certain pairs were statistically different ($p < 0.05$) as follows: Piezo-electric R50 (pairs 1/550 with RPs in the range 1/25–1/350, 1/450 with RPs in the range 1/25–1/50, 1/450 with 1/150 and 1/450 with 1/250). RLO (pairs 1/550 with RPs in the range 1/25–1/350, 1/450 with RPs in the range 1/25–1/250 and 1/450 with 1/350, 1/300 with 1/25). SIN (pairs 1/350 with RPs in the range 1/25–1/50, 1/300 with RPs in the range 1/25–1/100, 1/250 with 1/25–1/100 and 1/200 with 1/25–1/100).

In the ranges where the power consumption was relatively independent of RP (e.g. piezo-electric transducer, SIN, for pairs 1/550 with 1/25–1/450), efficient operation was possible by choosing any RP in this range.

4 Conclusions

In this paper, the power consumption was experimentally measured for electromechanical and piezo-electric transducers for three types of excitatory waveform for vibrotactile stimulation: R50, RLO and SIN. For both types of transducer, the average power consumption was determined as a function of RP at sensation thresholds for a group of 12 subjects.

Experimental results showed that power consumption using piezo-electric transducers was significantly lower, by two orders of magnitude, than that using electromechanical transducers. In particular, it was found that the average power was lowest for the fixed RLO at RP = 1/25 s in the case of the electromechanical transducer, requiring 25 μW to reach sensation threshold. In the case of the piezo-electric transducer, the lowest power consumption was obtained with an SIN waveform at RP = 1/250 s, requiring 0.21 μW to reach sensation threshold. It was observed that power consumption increased for lower and higher RPs relative to 1/250 s. In the case where the negative power from the previous cycle was not recovered to excite the piezo-electric transducer, the minimum power consumption of 1.5 μW resulted for the RLO at RP = 1/25 s.

These results confirm the inefficient energy conversion of the electromechanical transducer mentioned in KACZMAREK *et al.* (1991). To excite the skin at the same level, both transducers require two orders of magnitude difference in power. Reviewing the literature, we have not found published results with measured transducer power consumption. Instead, there are several papers where the power consumption has been estimated theoretically.

It was found that the power requirements in the electromechanical transducer were proportional to the PW, for most RPs, when rectangular pulse waveforms of 50% DCY were used. The current waveform followed the voltage waveform, and therefore the power consumption increased with PW. For the electromechanical transducer, the power consumption for the SIN waveform was higher than that for rectangular waveforms for all repetitions periods, as was shown in Fig. 4.

For the piezo-electric transducer, the SIN waveform required lower power to reach sensation thresholds for RP in the range 1/550–1/150 s, with a minimum at 1/250 s. The statistical analysis indicates that there is a significant difference in power consumption for RP in the range 1/350–1/200 s. As was shown in Fig. 3*b*, the current pulse in the piezo-electric transducer did not follow the voltage pulse width, and therefore there was no power consumption, even though the voltage pulse was on. This explains the results for the piezo-electric transducer shown in Fig. 4*a*, where power consumption for the R50 did not increase with RP. In the case where the negative power from the previous cycle was not recovered to excite the piezo-electric transducer, the minimum power consumption was found to be for RLO at RP = 1/25.

For a tactile display composed of an array of 12 × 8 electromechanical transducers, the minimum power required to reach sensation threshold was 2400 μW using RLO at RP = 1/25 s. If the same tactile display was built with piezo-electric transducers, the minimum power required to reach sensation threshold would be 20.2 μW, using the SIN waveform at RP = 1/250 s.

Appropriate design of the tactile display influences the operational cost, size and weight of the device, as well as the heat dissipation. These results allow the selection of an appropriate set of waveform parameters and estimate the actual power requirements for tactile displays using electromechanical and piezo-electric transducers.

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