# Large Displacement Haptic Stimulus Actuator using Piezoelectric Pump for Wearable Devices

Taisuke Kodama, Shintaro Izumi, *Member, IEEE*, Kana Masaki, Hiroshi Kawaguchi, *Member, IEEE*, Kazusuke Maenaka, *Member, IEEE*, and Masahiko Yoshimoto, *Member, IEEE*

***Abstract*— Recently, given Japan's aging society background, wearable healthcare devices have increasingly attracted attention. Many devices have been developed, but most devices have only a sensing function. To expand the application area of wearable healthcare devices, an interactive communication function with the human body is required using an actuator. For example, a device must be useful for medication assistance, predictive alerts of a disease such as arrhythmia, and exercise. In this work, a haptic stimulus actuator using a piezoelectric pump is proposed to realize a large displacement in wearable devices. The proposed actuator drives tactile sensation of the human body. The measurement results obtained using a sensory examination demonstrate that the proposed actuator can generate sufficient stimuli even if adhered to the chest, which has fewer tactile receptors than either the fingertip or wrist.**

## I. Introduction

Recently, wearable healthcare systems play an ever more prominent role in the aging society. Daily life monitoring is an important application of wearable healthcare systems to prevent lifestyle diseases, which have rapidly raised the number of patients and elderly people who require nursing care.

Many wearable devices have been developed in recent years (e.g., wrist watch type, adhesive patch type, and chest belt type). However, most such devices only provide a "sensing" function. If the device has an actuator to communicate with human body interactively (see Fig. 1), then the application area of wearable healthcare devices can be expanded as shown below.

- Inform a user of the timing of medicine or diet
- Alert for abnormal biosignal detection for diseases or conditions such as high-blood pressure or arrhythmia
- Support exercise by recording and analyzing the heart rate
- Notify a user of a high-risk, such as sedentary, lifestyle

In contrast with other wearable sensors, which require smartphone or other devices to communicate with users, the proposed device can inform these notifications directly. Therefore, the objective of this work is the implementation of a haptic stimulus actuator. However, two difficulties hinder the implementation of the actuator in wearable devices [1].

T. Kodama, S. Izumi, K. Masaki, H. Kawaguchi, and M. Yoshimoto are with the Graduate School of System Informatics, Kobe University, 1-1 Rokkodai, Nada, Kobe, Hyogo 657-8501, Japan (e-mail: kodama.taisuke@cs28.cs.kobe-u.ac.jp).

K. Maenaka is with the Graduate School of Engineering, University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2280, Japan.

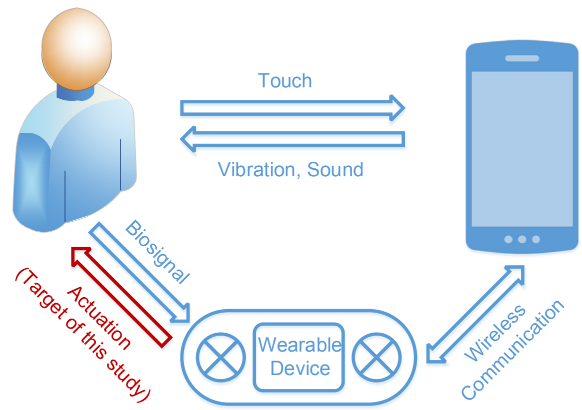


Fig. 1. Communications in wearable system.

The first is power consumption. Key factors affecting wearable system usability are miniaturization and weight reduction. Because the battery weight is a dominant characteristic of the wearable system, the battery capacity and power consumption must be limited to the greatest extent possible. The second hindrance is the tactile sense of the human body. The chest surface and the wrist are not as sensitive as a fingertip [2]. In other words, a large displacement is necessary for stimulation by the actuator. Consequently, we propose large displacement and a low power actuator solution in this work.

## II. Tactile Sensation and Conventional Actuators

To generate efficient tactile stimulation using the actuator, we considered tactile characteristics of the human body.

### *A. Cutaneous Receptors*

Tactile receptors of four kinds are distributed under the skin: SAI, SAII, FAI, and FAII [2]. They are classified by the adaptation speed and receptive field. Fig. 2 shows the relation between the stimulus frequency and the displacement threshold perceived by each receptor. The characteristics of each receptor are shown in Table 1. By integrating the stimulus information from each receptor, the human brain can recognize tactile sensations such as smooth and rough [3, 4].

As presented in Fig. 2, the FAII receptor is most sensitive to high-frequency stimulus. However, FAII and SAII receptors are fewer than FAI and SAI. Also the distribution of these receptors is not uniform. Although the experimentally obtained results of prior work [5, 6], as presented in Fig. 2, apply only to the palm of the hand, the wearable devices are worn mainly on the wrist or chest. These areas have a sparse

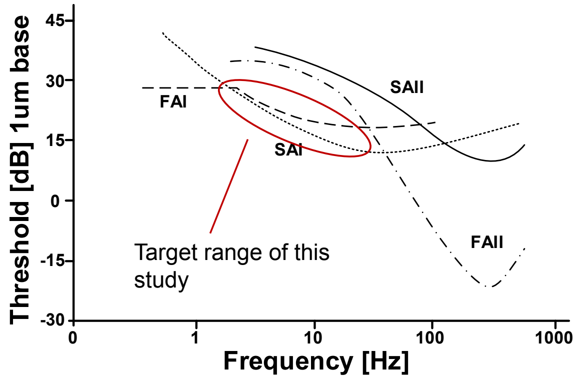


Fig. 2. Relation between stimulus frequency and sensitive threshold of displacement for each receptors. The original figure is presented in Ref. [5].

TABLE I. CHARACTERISTICS OF TACTILE RECEPTORS [2].

| | SAI | SAII | FAI | FAII |
|---|---|---|---|---|
| Adaptation Speed | Slow | Slow | Fast | Fast |
| Position | Shallow | Deep | Shallow | Deep |
| Breadth | Narrow | Wide | Narrow | Wide |
| Name | Merkel disc | Ruffini ending | Meissner corpuscle | Pacinian corpuscle |
| Frequency range | 0.4–100 Hz | 0.4–100 Hz | 10–200 Hz | 70–1000 Hz |
| Stimulus to react | Pressure | Pressure | Low-frequency | High-frequency |

receptor distribution compared with the palm. Therefore, we target FAI and SAI receptors with frequencies of 5–100 Hz.

## *B. Conventional Haptic Stimulus Actuators*

An eccentric rotating mass (ERM) is commonly used in mobile phones as the haptic stimulus actuator. A linear resonant actuator (LRA) is also used in smart watches such as the Apple Watch™. These actuators not only have high power consumption; they also have slow response.

A piezoelectric actuator (PZT) is used in modern mobile devices and tactile displays [7]. It has higher response speed and less power consumption than the ERM and the linear actuator. Moreover, it is suitable for miniaturization because it has a simple structure. However, it has only one shortcoming: the driving voltage becomes high to obtain high displacement.

When the PZT element is contacted to the skin of the chest, the required driving voltage to generate sufficient displacement of common piezoelectric actuator has been around 30 V or more in previous studies [8–12]. It is therefore difficult to ensure safety when the PZT element directly contacts the skin. The principal problem of PZT actuator in wearable devices is that the PZT element is directly contacted to the skin or the chassis of the device. In addition to the safety problem, the resonance frequency of PZT element is changed and the maximum displacement is degraded in this condition. The power efficiency of PZT actuator is degraded rapidly when the vibration frequency is turned away from the resonant

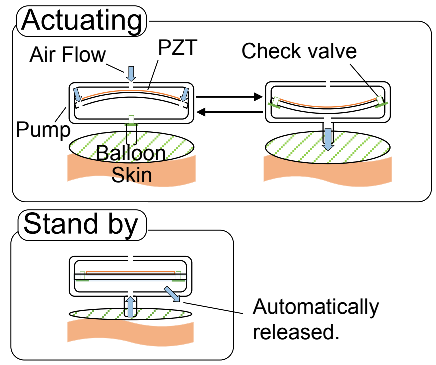


Fig. 3. Structure of proposed actuator using PZT pump.

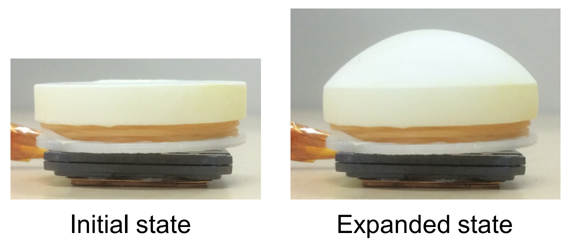


Fig. 4. Photograph of prototype actuator.

frequency. Consequently, sufficient displacement stimuli are necessary to realize driving voltage reduction.

## III. PROPOSED DESIGN OF HAPTIC STIMULUS ACTUATOR

To realize a large displacement actuator with efficient power consumption, we specifically examine a micro pump using PZT (PZT pump).

## *A. Structure*

Fig. 3 depicts the proposed actuator structure. The proposed actuator can stimulate the tactile using the variation of the pressure instead of the vibration. As depicted in Fig. 3, the PZT pump can generate air flow in one direction. Then, the difference of air pressure in pump chamber is generated using the deformation of PZT diaphragm. The air flow can be controlled using check valves [13].

A balloon of latex or silicone rubber is joined to the PZT pump outlet. The balloon is contacted to the skin. It expands according to the pump's actuation. Inner pressure is released automatically when the pump is stopped. Then, the PZT diaphragm in the PZT pump can be actuated with resonance frequency because only the balloon contacts the skin. Therefore, the proposed device can generate the large displacement with higher power efficiency compared with the conventional PZT actuator.

Fig. 4 portrays the prototype actuator using the PZT pump. The joint parts were designed in 3D editor and were printed with a 3D printer. The actuator has 10-mm height and 25 mm × 25 mm area. Fig. 5 presents the implementation image of the wearable device with the proposed actuator. The device consists of an electrocardiograph (ECG) sensor SoC, a wireless communication module, a battery, boosting circuits, and the proposed actuator. The estimated device dimensions are 40-mm height, 50-mm width, and 20-mm length.

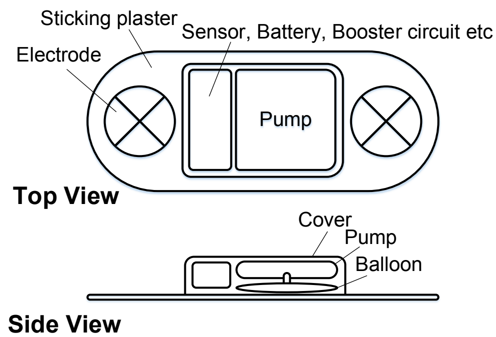


Fig. 5. Wearable device with PZT pump actuator.

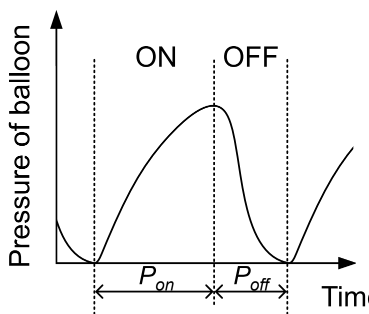


Fig. 6. Pressure control for stimulus generation.

### B. *Pump Control Method for Stimulus Generation*

The proposed actuator delivers a stimulus to the skin using pressure variation. Fig. 6 presents an image of the balloon internal pressure control. The PZT pump is driven periodically to generate the efficient stimulus to the skin, as presented in Fig. 2. Here, $P_{ON}$ and $P_{OFF}$ denote the pump driving duration and the pump standby duration. The inverse of ($P_{ON}$ + $P_{OFF}$) shows the frequency of the generated stimulus. The PZT pump is driven by the resonance frequency while $P_{ON.}$ In this work, we use the pump with 23.1-kHz resonant frequency. In contrast with the PZT actuator, the PZT pump can be driven outside of an audible frequency band. It can also act as a speaker when it is driven at an audible range frequency.

The $P_{ON}$ should be set longer than the $P_{OFF}$ because pressurization requires a longer time than the evacuation of air from the balloon. Fig. 7 shows the measured inner pressure of the proposed actuator during pressurization and evacuation. The driving voltage is set as 5–15 V. Fig. 7(a) shows the no-load condition. In Fig. 7(b), the balloon presses the skin of the user's arm.

As portrayed in Fig. 7, pressurization to the saturated pressure takes about three times longer than with the evacuation to air pressure in each condition. Given equal driving voltage, the required durations of the pressurizing to saturated pressure and the evacuation to air pressure depend on the balloon load condition, which is decided by the skin elasticity, which is pressed by the balloon of the actuator.

## IV. Performance Evaluation

Ideally, $P_{ON}$, $P_{OFF}$ and driving voltage should be optimized individually because elasticity differs according to the part of body, age, sex, and physical constitution. We assess these parameters here using an sensory examination.

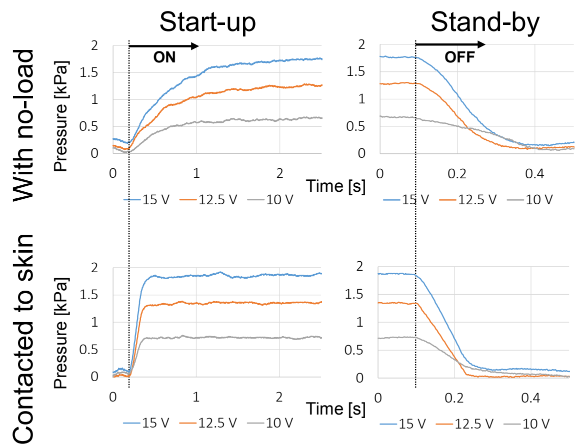


Fig. 7. Inner pressure transition of ballooon at start-up and stand-by: (a) with no-load and (b) contacted to skin conditions.

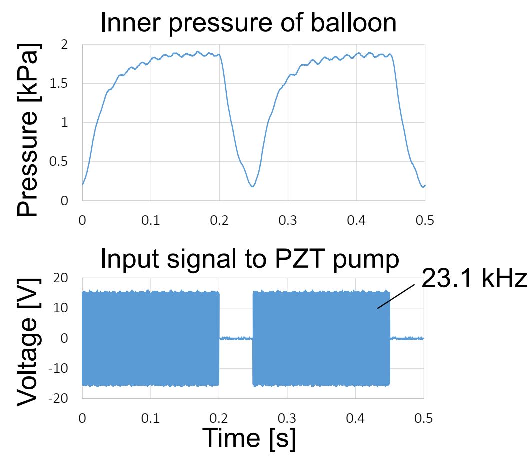


Fig. 8. Measured inner pressure of ballooon while tactile stimulus generation. The balloon is contacted to skin.

The examination assessed nine subjects (8 men, 1 woman) of age 22–25. The actuator was directly contacted to the fingertip, the wrist, and the left chest (underside of the collarbone). The subjects were covered their ears. They are instructed beforehand to make a gesture when they recognized the stimulus from the actuator. The PZT pump driving voltage is set as 2.5–15 V by 2.5 V steps. In each of steps, the pump is actuated for 5 seconds.

First, we set the durations of $P_{ON}$ and $P_{OFF}$ in Fig. 6 to 200 ms and 50 ms, respectively. The sensory examination results show that these values are the most sensitive setting when the actuator is contacted to the skin of the chest. This result also has a correlation with the experimentally obtained result of Fig. 7(b). The measured inner pressure of the balloon and the driving voltage are presented in Fig. 8. Then, the balloon is contacted to the left chest of a subject.

Next, the minimum required driving voltage to perceive the haptic actuation was evaluated. Fig. 9 depicts the experimental setup of the sensory examination. Fig. 10 shows the examination results obtained from nine subjects.

Because the fingertip is one of the most sensitive parts of the human body, all subjects can perceive the haptic actuation with driving voltage of 7.5 V or more. However, 12.5 V or higher voltage must be used when the actuator is contacted to the skin of the wrist or the chest. This result agrees with our expectation, as shown in Section 2.

Results for the proposed actuator with the eccentric rotating mass (ERM) and the linear resonant actuator (LRA) are shown in Table 2. Because our target is the wearable device, the actuator power is supplied by the battery. We assume a lithium polymer battery with 3.7-V supply voltage and 110-mAh capacity. The proposed actuator requires voltage boosting circuits to generate 12.5-V or 15-V supply voltage, but it has smallest current consumption and largest displacement even contacting the skin. Current consumption is the most important index in the battery-driven system.

Another benefit of the PZT pump is the electromagnetic noise, which is much less than the ERM. This is an important point for wearable sensors because the sensor circuits of the wearable sensors are sensitive to noise. Furthermore, the noise of this actuator has a much higher frequency compared with bio-signals such as ECG because the actuator is driven by the resonance frequency of the PZT pump. Therefore, it can be removed easily using a low-pass filter.

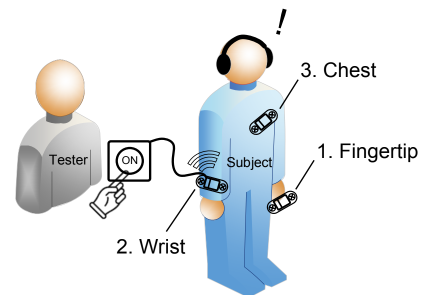


Fig. 9. Experimental setup.

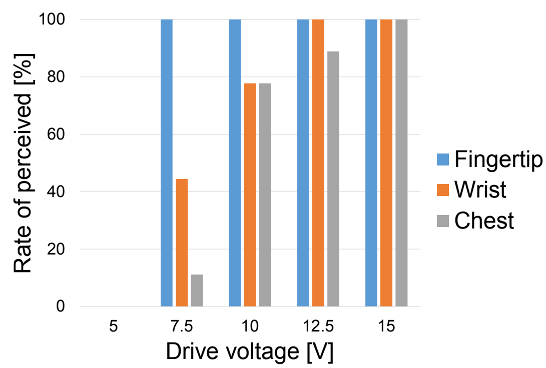


Fig. 10. Experimental result of required voltage to perceive haptic actuation.

TABLE II. COMPARISON OF HAPTIC STIMULUS ACTUATORS

| | Proposed actuator | | ERM (LBV10B-009) | LRA (LD14-002) |
|---|---|---|---|---|
| Driving voltage | 12.5 V | 15 V | 3.7 V | 3.7 V |
| Driving current consumption | 36.8 mA | 42.4 mA | 75 mA | 120 mA |
| | (Including voltage boosting circuits) | | | |
| Displacement w/ load | large | | medium | small |
| Size | 20 mm × 20 mm | | 10 mm × 10 mm | 12 mm × 14 mm |

## V. CONCLUSION

For this study, we designed the haptic stimulus actuator using the PZT pump for wearable devices. The sensory examination results show that the required minimum driving voltage to perceive haptic actuation is 12.5 V. Then, the proposed actuator consumes 36.8 mA on average including the boosting circuits from 3.7-V battery output. Compared with other actuators, the proposed actuator has large displacement and smaller current consumption, even if contacted to the skin. However, it is not small. Because size is also an important factor of the wearable device, that point should be improved in future work. The required voltage and the actuator size are decided by the PZT pump specifications. Consequently, it can be improved using MEMS technology and characteristic improvement of the PZT element.

## REFERENCES


[1] A. S. Mandayam, and B. Cagatay "Haptics in virtual environments: Taxonomy, research status, and challenges," *Haptic Displays in Virtual Environments and Computer Graphics in Korea*, vol. 21, cp. 4, pp.393–404, July 1997.

[2] Morton A. Heller, and William Schiff. "Sensory and Physiological Bases of Touch," *The Psychology of Touch*, cp. 2, pp.23–60.

[3] B. L. Munger, "Patterns of organization of peripheral sensory receptors," *Principles of receptor physiology*, pp.523–556.

[4] J. P. Nafe, and K. S. Wagoner, "The nature of pressure adaptation," *Journal of General Psychology*, vol. 25, pp.323–351.

[5] S. J. Bolanowski, G. A. Gescheider, R. T. Verrillo, and C. M. Checkosky, "Four channels mediate the mechanical aspects of touch," *Journal of the Acoustical Society of America*, vol. 84 no. 5, pp.1680–1694, 1988.

[6] Jones, Lynette A., and Susan J. Lederman. "Tactile Sensing," *Human Hand Function*, Oxford: Oxford UP, cp. 3, pp.44–74, 2006.

[7] Dong-Soo Kwon, Tae-Heon Yang, JoonYeon Cho, "Trend & prospects of haptic technology in mobile devices," *Symposium on Industrial Electronics (ISIE)*, IEEE, pp.3778–3783, July 2010.

[8] F. Casset et al., "Low voltage actuated plate for haptic applications with PZT thin-film," *International Conference on Solid-State Sensors, Actuators and Microsystems*, pp.2733–2736, June 2013.

[9] H. Feth et al., "Design and characterization of a low-voltage piezoelectrically actuated polymer membrane," *International Conference on Solid-State Sensors, Actuators and Microsystems*, pp.470–473, June 2011.

[10] P. Laitinen, and J. Maenpaa, "Enabling mobile haptic design: piezoelectric actuator technology properties in hand held devices," *International Workshop on Haptic Audio Visual Environments and their Applications (HAVE 2006)*, IEEE, pp.40–43, 2006.

[11] M. Wagner et al., "Novel Low Voltage Piezoactuators for High Displacements," *Journal of Electroceramics*, vol. 14, pp.231–238, 2005.

[12] Qi Wang, and V. Hayward, "Compact, Portable, Modular, High-performance, Distributed Tactile Transducer Device Based on Lateral Skin Deformation," *Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp.67–72, 2006.

[13] H. T. G. van Lintel, F.C.M. van De Pol, and S. Bouwstra, "A piezoelectric micropump based on micromachining of silicon", *Sensors and Actuators*, vol. 15, no. 2, pp.153–167, Oct. 1988.