Tension-Based Wearable Vibroacoustic Device for Music Appreciation

Yusuke Yamazaki(✉), Hironori Mitake, and Shoichi Hasegawa

Tokyo Institute of Technology, Tokyo, Japan
yus988@haselab.net

Abstract. We propose a new vibroacoustic device that consists of a string and two motors, called a wearable tension-based vibroacoustic device (WTV). To demonstrate the superior performance of the WTV over conventional wearable devices, which contain vibrators, we conducted two experiments. First, we measured the amplitudes of vibration of the skin while subjects wore the WTV and Haptuators. We found out that WTV is better than Haptuators at transmitting low-frequency waves over a wide range throughout the body. Second, we examined subjective evaluations of acoustic vibration for both devices. Almost all participants considered the WTV to be a better option as a vibroacoustic device. We thus conclude that the WTV is a good option for applications requiring high-quality and strong stimuli, such as listening to music and virtual-reality gaming.

1 Introduction

When listening to music, we can feel excitement not only because of the sounds that we hear but also the vibrations that we feel in our body. Such a case is attending a live music performance, which can be more exciting than listening to the same music at home. The heightened excitement might be due to a number of factors, such as the sense of unity with other fans and the vibration of the music transmitted through the body. This paper focuses on this vibration, known as acoustic vibration.

Acoustic vibration is a phenomenon perceived by our somatosensory system. The joy of listening to music is enhanced by low-frequency vibrations. To simulate such vibrations for the benefit of music listeners, indoor vibroacoustic devices (some of which are referred to as body sonic systems) have been developed [1]. Conventional vibroacoustic devices take the form of chairs or beds with transducers that are located along the user's back and enhance the musical experience. In addition, the effects of these vibroacoustic devices relating to relaxation and the suppression of pain are appreciated [2–5] and many dental clinics and relaxation facilities have thus introduced such systems. Similar systems, which transmit sound vibration effects, are used in entertainment facilities such as theme park attractions and 4DX movie theaters.

Despite their effects, vibroacoustic devices are only used in special facilities and are not yet popular in terms of the daily experience of listening to music.

F. Bello et al. (Eds.): EuroHaptics 2016, Part II, LNCS 9775, pp. 273–283, 2016.
DOI: 10.1007/978-3-319-42324-1_27

This might be explained by the size, cost, and usability of such systems. The present paper proposes a light, wearable and effective vibroacoustic device that contains a string and two motors and can be used as easily as earphones. We believe it has the potential to become a new standard tool for music appreciation.

1.1 Previous Works

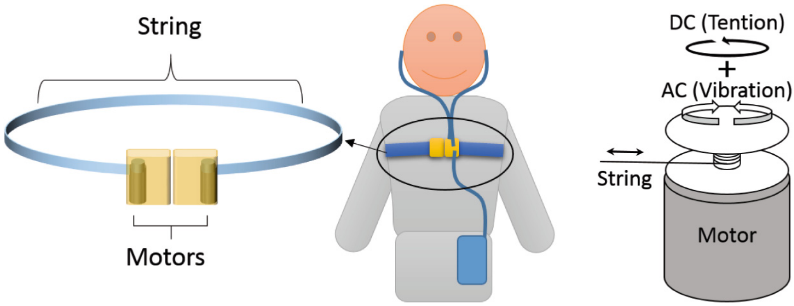
There are wearable products that can display the vibration of music. One example, SUBPAC [6], has vibration transducers and can be worn as a backpack. The user can feel a vibration all along his/her back. Another, called Woojer [7], is a square device with a small vibrator inside. It is easy to wear and allows the user to enjoy acoustic vibrations. However, both products have problems, namely SUBPAC is too big for daily use and Woojer is poor at transmitting a vibration to a wide area of the body. There is trade-off between usability and vibration transmission. Similar products face the same problems.

Another problem is that vibrators such as the Haptuator vibrate well at a relatively high frequency (around 150 Hz) but not at a low frequency. This is a problem, as the skin is less sensitive to vibrations than the ear [8] and the rhythm of a tactile sensation is modulated by the auditory sensation [9]; the acoustic vibration thus controls the musical rhythm. According to a previous study [10], bass-ranged instruments dictate musical rhythms, and vibroacoustic devices are thus required to play low frequencies with high amplitudes. A sufficiently large amplitude requires the device to be large, meaning that the device cannot be worn by the user.

1.2 Proposal

To overcome the limitations of the described vibroacoustic devices, we propose a new vibroacoustic device (Fig. 1), namely a wearable tension-based vibroacoustic device (WTV) including motors and a string. The string is worn on the user's body and pulled by two motors (Fig. 1a) whose current is controlled by an audio amplifier. When music signals are detected, the motor shafts begin to rotate and the rotational directions change quickly. The motors transmit vibration to the string fitted on a pulley (Fig. 1b) and the user then feels the vibration from the string. The proposed device has two important advantages over vibrators. First, it can transmit vibration to a wider area of the body than conventional vibrators owing to the difference in the contact region between the string and vibrator. While vibrators only contact limited surfaces of the user's body, the string can be worn around the body. Second, DC motors are good at playing low frequencies. Small vibrators are limited in terms of their linear stroke, which in turn limits the amplitude of low-frequency vibration. Meanwhile, motors of any size have no restriction because they can rotate infinitely.

To demonstrate the advantages of the WTV over conventional wearable vibroacoustic devices, two experiments were carried out using Haptuators as a



(a) How the WTV is worn (b) How the WTV works

Fig. 1. Image of the WTV

representative conventional device. First, in a quantitative experiment, we measured the amplitude of the vibration on the skin where the WTV or Haptuator is attached. Second, in a subjective experiment, we investigated subjective impressions of music application under three conditions: sound only, sound with conventional Haptuator vibrators, and sound with the proposed WTV.

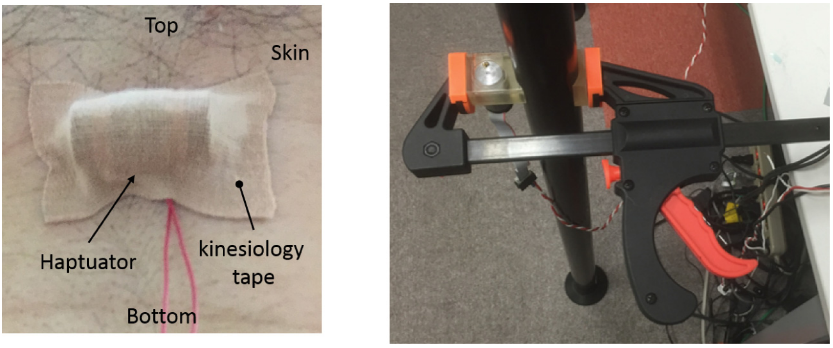
2 Evaluation

2.1 Quantitative Experiment

We used an accelerometer and measured the amplitude of vibration (hereafter referred to as the amplitude) at sampling points to find out how the vibration is transmitted from the WTV or Haptuator to the body. We used two frequencies of vibration, 30 Hz and 150 Hz. We recruited five male participants aged 23 to 33 years. During the experiment, subjects' chests were exposed. During the Haptuator test, we fixed two Haptuators using double-sided tape and kinesiology tape (Fig. 2a). We placed one Haptuator on the front of a participant and one on the back at the same level and allowed them to vibrate simultaneously. During the WTV test, we fixed the motors on poles (Fig. 2b) and wrapped the string around a participant (Fig. 3).

Materials and Methods

Vibration. We used 30-Hz (regarded as low frequency) and 150-Hz (regarded as high frequency) sinusoidal waves for vibration. The frequency of 30 Hz is the resonance frequency of Meissner's corpuscle [11]. (In fact, we must consider hair follicle receptors because there are hair follicle receptors instead of Meissner corpuscles in the area of hair-bearing skin. However, the characteristics of Meissner corpuscles and hair follicle receptors are similar. [12]) A frequency of 150 Hz is the upper-limit frequency of a general acoustic vibration system [13,14]. We used



(a) Setup of a Haptuator (b) Setup of the WTV

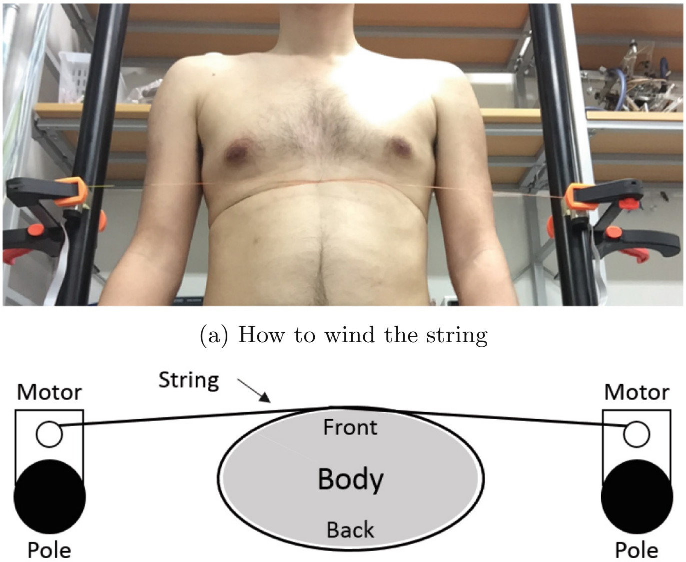
Fig. 2. Experimental setups of the Haptuator and WTV

an audio amplifier (LP-2020A+, Lepai) to generate waves in the experiments. The amplitude of the waves was fixed at a root-mean-square (RMS) voltage of 183 mV. The two Haptuators consumed a total of 5.48 mW of electrical power at 150 Hz and 2.79 mW at 30 Hz, while the WTV consumed 4.60 mW at 150 Hz and 1.79 mW at 30 Hz. The power consumption varied because we fixed the voltage of the audio amplifier output (620 mV peak to peak).

Devices. We used two motors (Model number 220429, Maxon Motor) and a string (Ultra 2 Dyneema # 8, YGK YOZ-AMI Co., Ltd.) for the WTV. The motors had a diameter of 24 mm. The pulley had a diameter of 19 mm and weighed 2.64 g. We used two Haptuators (Tl-002-14R, Tactile Labs) as a representative conventional vibroacoustic device. Haptuators were used because of their high efficiency, because their mechanism of transmitting vibration and contact condition are about the same as those of commercial devices presently available, and because they are wearable. The regular torque of the motors was 5.54 mNm.

Experimental Conditions. We fixed each Haptuator to the body using double-sided tape (NW-K15, NICHIBAN) and kinesiology tape (NKHB5, Nitto Medical). We first placed double-sided tape on the Haptuator and stuck the Haptuator to the body. We then covered the Haptuator and body with kinesiology tape (Fig. 3a). The Haptuator was thus stably attached to the body. We fixed the two motors of the WTV to two tension poles (Autopole 032B, Manfrotto) instead of the body because we wanted to eliminate the vibration transmitted directly from the motors. We therefore restricted the transmitted vibration to only the vibration transmitted by the string to observe the difference in performance between the Haptuators and WTV. The distance between the two poles was 700 mm. The heights of the fixed motors were adjusted to the height of the string on the body, which was also the height of the Haptuators.

Sampling Points. We chose four regions for sampling: the chest, back, lower abdomen, and waist. (Hereafter, tC denotes the chest, tB the back, tLA the



(a) How to wind the string

(b) Illustration of the experimental conditions for the WTV

Fig. 3. Experimental conditions for the WTV

lower abdomen, and tW the waist.) The height of the vibration point on tC and tB is immediately below the chest, while that on tLA and tW is 10 mm above the navel.

Analysis. We made measurements using an accelerometer (KXR94-2050, Kionix) and recorded data using a data logger (NR-2000, KEYENCE) with a sampling rate of 1 kHz. Each trial was 3 s in duration. After correcting for the offset, we calculated the RMS acceleration.

2.2 Subjective Experiment

We investigated the subjective evaluation of acoustic vibration presented by the WTV or Haptuators. We recruited 10 participants, comprising seven males and three females with ages ranging 23 to 33 years. Five of the male participants had also participated in the quantitative experiment. We first asked subjects to listen to music without vibration. We then placed the WTV or Haptuators on the subjects and played the music again. After participants gave subjective evaluation scores, they removed one device and put the other device on. Each participant thus had a chance to experience both devices. We let the participants change from one device to the other at any time at their discretion. The devices were only located at the chest. Participants wore thin clothing.

Materials and Methods

Music. We chose two types of music: jazz music (Tribal Tech, Nite Club, 5:25–5:55), considered as intensive music; and piano music (Chopin, Fantaisie Impromptu, 0:34–1:04), considered as calm music.

Questionnaire. A questionnaire was used to compare the experiences of listening to music with the WTV and with the Haptuators. For each situation, we asked the participants whether they liked or disliked the experience, whether the experience was rhythmical, whether they felt a sense of unity with the music, and whether they felt present at the performance. We used a visual analogue scale for evaluation and measured the length from the zero-point at the middle of the scale to the mark made by the participant. A score of zero indicates there was no change in the impression of the music due to the WTV or Haptuators, while a score of ± 5 indicates extreme positive (+) or negative (−) changes.

3 Results and Discussion

3.1 Comparison of the Amplitudes of Vibrations Transmitted by the WTV and Haptuators

Results. We investigated the difference in amplitude (i.e., acceleration) between the WTV and Haptuators. We then compared the amplitudes for the same location of a sampling point and the same frequency of vibration. We obtained average values for five subjects and conducted a (two-sided) Welch t-test. Figure 4 shows the measuring points having significant differences in amplitude between the WTV and Haptuators. We found that 10 of 18 sampling points on tB at 150 Hz and 15 of 18 sampling points on tB at 30 Hz had significant differences. The amplitude of the WTV was greater than that of the Haptuators at 150 Hz, and the amplitude of the Haptuators was greater than that of the WTV at 30 Hz.

Figure 5 shows the amplitude at each sampling point. Note that at 150 Hz, the WTV transmitted a vibration with acceleration higher than 5 m/s^2 at L-C and R-C (defined in the caption of Fig. 4) on tC and tLA. Meanwhile, the WTV transmitted a vibration with a maximum amplitude of only 1–2 m/s^2 and most values of amplitude were less than 1 m/s^2 on the participant's back. The Haptuators transmitted vibrations higher than 7 m/s^2 at C-C on tC, tLA, and tW and higher than 2 m/s^2 at B-L and B-R on tC, which were located near the ribs. At 30 Hz, the WTV transmitted vibrations higher than 2 m/s^2 at all points on tLA. The WTV also transmitted vibrations of 3–5 m/s^2 at C-L, 5–7 m/s^2 and more than 1 m/s^2 at all other points on tC. However, there were no points at which the vibration exceeded 1 m/s^2 on the participant's back. The Haptuators transmitted vibrations of 2–3 m/s^2 at C-C on tC and at C-C and C-R on tLA, but vibrations at other points were lower than 2 m/s^2.

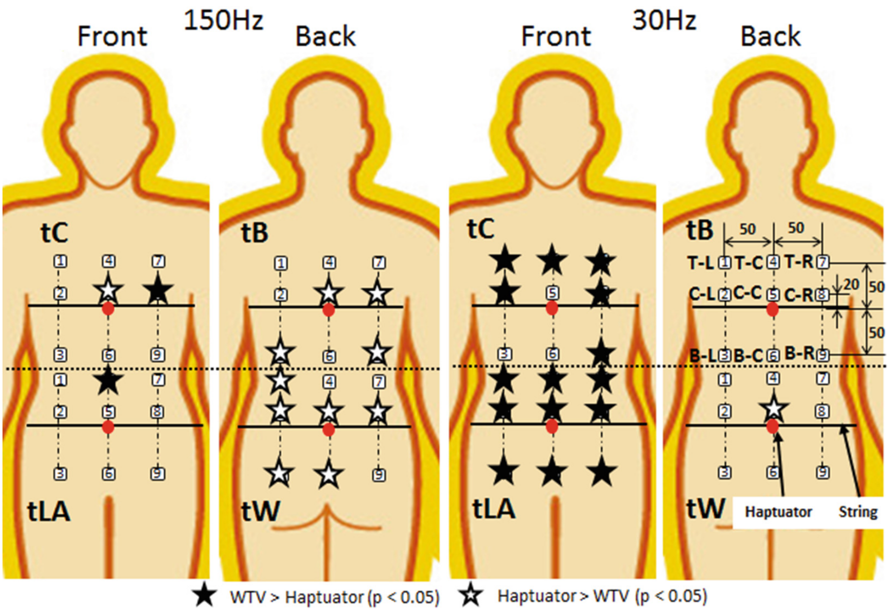


Fig. 4. Significant differences in amplitude between the WTV and Haptuators. tC: chest, tB: back, tLA: lower abdomen, tW: waist T-L: Top-left, C-L: Center-left, B-L: Bottom-left, T-C: Top-center, C-C; Center-center, B-C: Bottom center, T-R: Top-right, C-R: Center-right, B-R: Bottom-right A red circle at the center shows the location of a Haptuator. The black horizontal line represents the location of the string of the WTV (Color figure online)

Discussion. The experimental results show that the WTV is better than the Haptuators at transmitting the 30-Hz vibration, and transmits to a wider area at the front of the body regardless of frequency. This is because of the characteristics of the vibrator, motors and Haptuators. As previously mentioned, a motor provides good vibration at low frequencies and the Haptuator provides good vibration at high frequencies from a mechanical point of view. Meanwhile, the WTV was adequate for transmitting a high-frequency vibration because there were no significant differences in vibration amplitude at the front of the body except for C-C on tC. For the points at C-R on tC and T-C on tLA, the amplitude of the WTV was greater than that of the Haptuators.

The last finding is explained by the string tightly wrapping the body, such that the affected area is larger than that of the Haptuators. This is also supported by the results shown in Fig. 5. All points on the front of the body except for C-C, B-L and B-R on tC and C-C on tLA experienced greater vibration from the WTV at 150 Hz. The reason for this seems to be that the vibration transmits through the ribs.

However, the WTV does not sufficiently vibrate the back of the body. This is because of the way that the string was wound around the body as shown

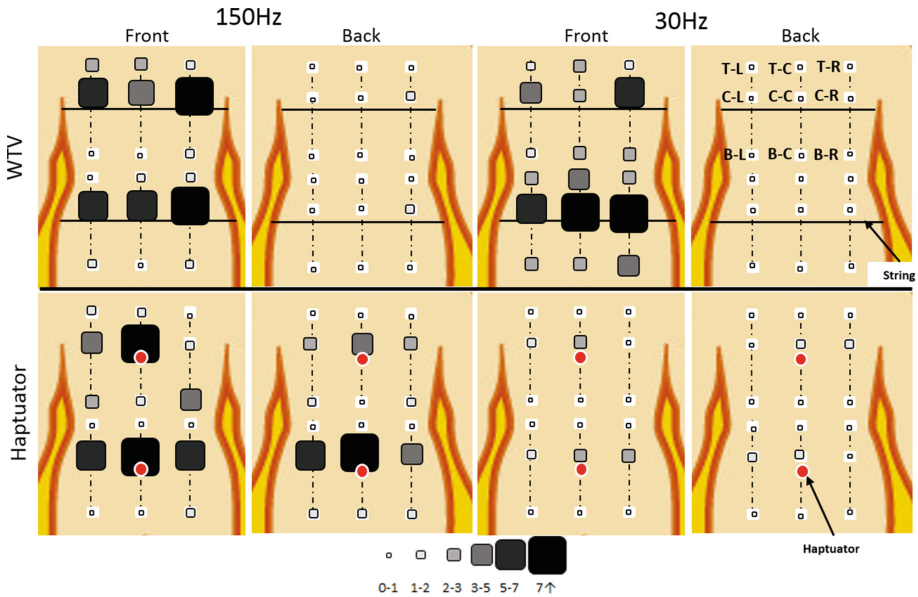


Fig. 5. Amplitudes represented by the size and color of a square at each sampling point (m/s^2)

in Fig. 2. With such winding, vibration from the bilateral motor reaches first the front and then the back. It is thus likely that the vibration is extremely attenuated at the front, which must be considered. We are investigating a better way of winding the string around the body to achieve better performance.

3.2 Subjective Experiment

Results. Average evaluation scores given by the 10 subjects are shown in Fig. 6. In the case of jazz music, there was a significant difference (p-value less than 0.05) between the scores of the WTV and Haptuators for questions B and C and a marginally significant difference (p-value between 0.05 and 0.1) for question D. In the case of piano music, there was a significant difference for question C and a marginally significant difference for questions A and D. All scores for the WTV were better than those for the Haptuators on average. In terms of counting the negative scores, which indicate that the vibration was perceived to be obstructive, there was one negative score for question B and one negative score for question D when piano music was played with vibration from the WTV. Meanwhile, there were three negative scores for question A, four for question B, three for question C, and three for question D when jazz music was played and one negative score for question A, three for question B, three for question C, and two for question D when piano music was played with vibration from the Haptuators.

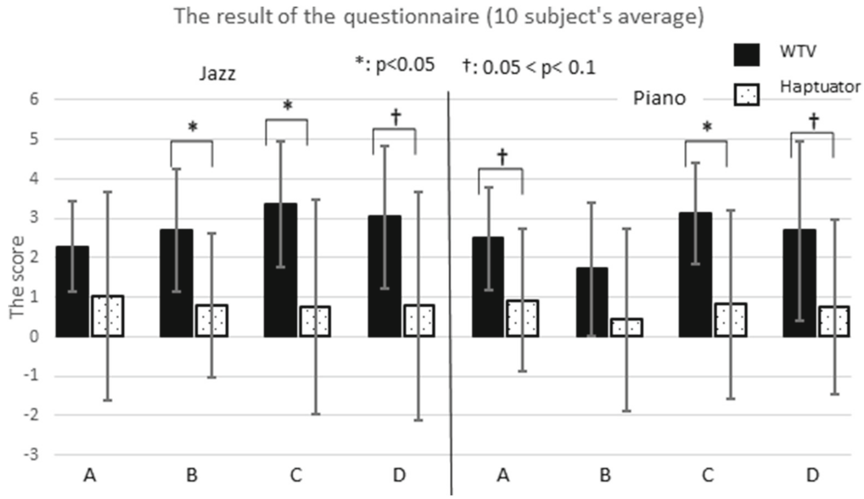


Fig. 6. Results of the questionnaire. A: like or dislike, B: rhythmical sensation or not, C: a sense of unity or not, and D: a sense of being present or not.

Discussion. The average scores and fewer negative scores given in the subjective evaluation show that the WTV performs better than the Haptuators as a vibroacoustic device. There were no significant differences in responses to question A for either type of music because even though participants preferred the WTV, they also liked the vibration of the Haptuators. This result demonstrates the usability of vibroacoustic devices. There was a significant difference in responses to question B when jazz music was played but not when piano music was played. It seems that the quality of music that includes a bass drum that keeps the rhythm of the music was more enhanced by the WTV. Most participants who gave a high score stated that they noticed and liked the vibration of the bass drum. There were significant differences in responses to question C for both types of music. It appears that the vibration of the WTV is more detailed than that of the Haptuators. In fact, some participants stated that the WTV transmitted the vibration of music more clearly than the Haptuators. This could be because of the tightness of the wrapping of the string of the WTV around the body. When using the Haptuators, the force of attachment cannot be changed. However, the tightness of the WTV is continuously affected by the frequency of vibration, and participants could thus detect the difference in frequency more clearly than they could when wearing the Haptuators. Finally, there were no significant differences in responses to question D for either type of music. Some participants said the experience cannot be compared with a concert or a live performance because they felt the vibration only on part of the body, the chest. It thus seems that acoustic vibration cannot be simply compared with the experience of a concert or live performance.

We also received feedback about the music we played in the experiment. Four participants liked the jazz music only, three liked the piano music only, and three liked both. Those who liked jazz said they felt the rhythm of the jazz music because the vibration modulates, especially in the case of the sound of the bass drum. However, the piano music did not do as well because it had a constant vibration and no rhythm. Those who liked only piano music disliked jazz music because it includes many sounds from different instruments and they could not clearly connect the vibration with the sound. In the case of piano music, there is only one sound, and it is thus easier to connect the sound and vibration. Accordingly, we need to consider which sound to present in experiments because of individual preferences for music.

4 Conclusion

We found that the WTV outperforms Haptuators as a vibroacoustic device. In a subjective experiment, almost all participants thought that the WTV performed better than Haptuators, especially in terms of feeling rhythm and feeling a sense of unity with the music. It is believed that this can be explained by the WTV transmitting a higher amplitude vibration at low frequency to a wider range of the body than the Haptuators, as found in a quantitative experiment. Additionally, the WTV is able to transmit high-frequency vibration. It is possible to overcome the trade-off of the usability and area of transmission of vibration using the WTV. However, we found that the WTV cannot transmit vibration sufficiently to the back side of the body, on tB and tW. This is because of the way that the string is wound around the body. We therefore need to investigate the best way to wind the string around the body.

Acknowledgements. We thank Erik Lopez and Ding Haiyang for improving the manuscript.

References

1. Komatsu, A.: Method for expressing vibratory music and apparatus therefor, 9 April 2002. US Patent 6,369,312
2. Patrick, G.: The effects of vibroacoustic music on symptom reduction. IEEE Eng. Med. Biol. Mag. **18**(2), 97–100 (1999)
3. Naghdi, L., Ahonen, H., Macario, P., Bartel, L.: The effect of low-frequency sound stimulation on patients with fibromyalgia: a clinical study. Pain Res. Manage. **20**(1), e21–e27 (2015)
4. Marit Hoem Kvam: The effect of vibroacoustic therapy. Physiotherapy **83**(6), 290–295 (1997)
5. Boyd-Brewer, C.: Vibroacoustic therapy: sound vibrations in medicine. Altern. Complement. Ther. **9**(5), 257–263 (2003)
6. SUBPAC®, 8 February 2016. http://thesubpac.com/
7. Woojer®, 8 February 2016. http://get.woojer.com/

8. Verrillo, R.T.: Vibration sensation in humans. Music Percept. Interdisc. J. **9**(3), 281–302 (1992)
9. Bresciani, J.P., Ernst, M.O., Drewing, K., Bouyer, G., Maury, V., Kheddar, A.: Feeling what you hear: auditory signals can modulate tactile tap perception. Exp. Brain Res. **162**(2), 172–180 (2005)
10. Hove, M.J., Marie, C., Bruce, I.C., Trainor, L.J.: Superior time perception for lower musical pitch explains why bass-ranged instruments lay down musical rhythms. Proc. Nat. Acad. Sci. **111**(28), 10383–10388 (2014)
11. William, H.T., Darian-smith, I., Hans, H.: The sense of flutter-vibration: comparison of the human capacity with response patterns of mechanoreceptive aff erents from the monkey hand1 (1968)
12. Wood, A.W.: Physiology, Biophysics, and Biomedical Engineering. CRC Press, Boca Raton (2012)
13. Goldfarb, B.S., Fisher, J.D.: Acoustic entertainment and therapy systems for water fixtures, 2 July 1998. WO Patent App. PCT/US1997/003,710
14. Vibroacoustic mattress, 22 July 2015. CN Patent 204,483,597