# Bone Conduction as Sensory Feedback Interface: A Preliminary Study

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*Abstract*— **Non-invasive sensory feedback is a desirable goal for upper limb prostheses as well as in human robot interaction and other human machine interfaces. Yet many approaches have been studied, none has been broadly deployed in upper limb prostheses. Bone conduction has the potential to excite an effect known as osseoperception and therefore provides a novel sensory interface. This paper presents the preliminary results of our study into the temporal parameters of a sensory feedback interface utilizing vibrotactile stimulus onto the ulnar olecranon representing a non-invasive sensory feedback interface. Three different tests are performed to establish the characterizing parameters of the interface; perception threshold, sensation discrimination and reaction time. Our results are similar to the results obtained for invasive bone conduction. The perception threshold for lower frequencies is small and therefore allows using small transducers with low power consumption. The sensation discrimination shows comparable results as reported in existing literature as well as the reaction time for the amputee is within the same range.**

## I. INTRODUCTION

Providing the user with sensory feedback is a long lasting and much desired goal in prostheses for upper and lower limb [1] [2]. Sensory information measured at the various local points of the prostheses need to be relayed back to the user by appropriately stimulating the senses, such as the tactile perception of the human on the remaining limb or other points of the body.

Invasive and non-invasive approaches for providing feedback to the users have been investigated in the past [3] [2]. Invasive approaches such as implanted nerve electrodes have great potential but are only applicable and desirable to a subset of the amputees due to surgical risks for patients and potential limited lifetime of electrodes [2][4][1][5]. Non-invasive stimulation is therefore believed to be very important in the near future to reduce surgical risk as well as to improve accessibility [1]. Non-invasive feedback is also desirable in a broad range of research fields with applications in human robot interaction [6] and general in human machine interfaces (HMI) [7].

Common non-invasive feedback systems have been established using electrotactile, vibrotactile and mechanotactile feedback on the skin [3]. As stated in [3], the perception of electrotactile as well as vibrotactile stimulation on the skin varies with the location of applied contact. Mechanotactile feedback, often described as an object pushing in a direction normal to the skin, is often by design bulky and power consuming [4]. Vibrotactile feedback on the skin furthermore depends on how hard the transducer is pressed against the skin and is limited due to its comparably long delay time of up to 400 ms [3].

Vibrotactile feedback through the bone, also called bone conduction, can address the previous mentioned issues and has not been studied in this context. In the unimpaired human sensory system, tactile stimuli take 14 - 28 ms to reach cuneate nucleus [8]. Therefore, a maximum system latency of 3 - 5 ms should be achieved for effective volitional use and less than 300 ms to attain self-attribution [8]. In bone conduction experiments on osseointegrated subjects in [9], a latency as little as 100 ms was achieved for the stimulation setup. An evaluation of state of the art bone conduction transducers like the B81 transducer, as used in [9], shows a possible improvement towards a latency of 15 ms and less [10]. In contrast to vibrotactile feedback on the skin, in [11] it was shown that the sensation threshold for such an interface was not dependent on the static force used to apply the transducer to the bone. The usable bandwidth of vibrotactile feedback on the skin lies in the range of 50 - 300 Hz [12]. In bone conduction, a range of 100 - 6000 Hz is shown [9]. Both senses, auditory and tactile, can be stimulated via bone conduction and are perceived in the range of 100 - 1500 Hz [9]. Vibrotactile feedback on the bone, as shown in [9], involves two sensory modalities, auditory and tactile sensation. This leads to a shorter reaction time as well as a better frequency discrimination in the frequency range where both senses are involved.

Non-invasive bone conduction as sensory feedback interface, involving auditory as well as tactile sensation, is therefore believed to offer a higher bandwidth, less power consumption due to smaller sensation thresholds, no static force dependency and a better self-attribution due to smaller transducer delay times. This paper shows a first insight into the capabilities of a non-invasive sensory feedback interface via bone conduction. Three important temporal parameters are determined in a psychometric experiment, showing the capabilities of a non-invasive version of such an interface. The transducer is placed on the bony landmark of the elbow onto the ulnar olecranon, which is the proximal end of the ulna loacated at the elbow.

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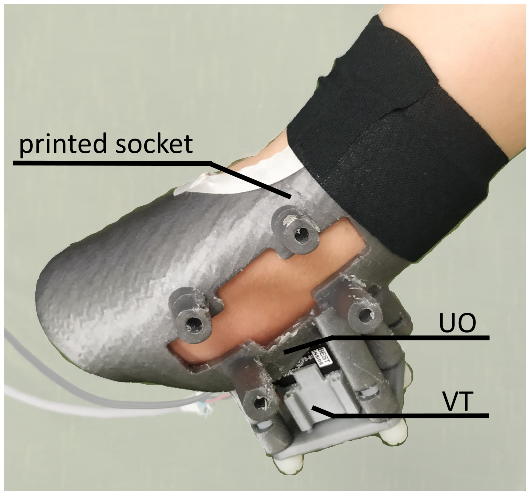


Fig. 1: The 3D printed socket for amputees is shown. It is printed as one piece whilst for able-bodied subjects split in half. It is equipped with the B81 vibrotactile transducers (VT) mounted onto a plate fixed with four screws to adjust the static force onto the ulnar olecranon (OT), which is measured using a FSR sensor. The amputee socket is fixed using kinesio tape.

## II. METHODS

The experiment was conducted with 2 able-bodied subjects (2 male; age 28.5 $\pm$ 2.1 years) and one amputee (male; age 21 years). All subjects read the plain language statement and signed the consent form approved by the Ethics Committee of the University of Melbourne (Ethics Id 1852875.1).

The transducer (B81 from Radioear) was calibrated using an Artificial Mastoid (4930 from Brüel & Kjære) applying it with a static force of 5.4 N. The audiometer (GSI 61) was switched to bone conduction and to Ext A input to pass through the signal from the frequency generator, Figure 2. The input signal to the audiometer is limited to 1V and the frequency generator set to high output impedance. The force sensitive resistor (FSR), Interlink Electronics 402 Round Short Tail, is placed between the transducer

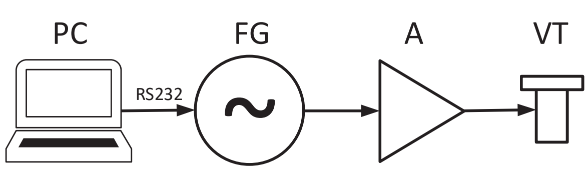


Fig. 2: Block scheme for controlling the stimulation parameters of the vibrotactile transducer (VT) via personal computer (PC) connecting via RS232 to a frequency generator (FG) and a audiometer (A) as amplifier.

Fig. 3: Test setup showing the subject seated in front of the table in the audio test booth. The amplifier and frequency generator as well as the Arduino are placed to the left and the notebook in front.

and the mounting plate with an effective area of 1.33 $cm^2$ . The FSR Sensor is implemented as the upper resistor in a voltage divider with a 3.3 $k\Omega$ resistor, the voltage drop measured using a microcontroller (Arduino Mega 2540) and the result read via USB using Matlab®. The calibration was done using [0.35 0.5 0.7] kg weights and linear interpolation. Application force was set manually with screws in the beginning of the experiment to be greater than 5.4 N. To press the transducers against the ulnar olecranon, a holder is needed. Therefore a socket is designed for each subject, see Figure 1. The arm/residual limb of each subject was 3D scanned using the Artec Eva Scanner®. After scanning data was fused using Artec Studio®. To achieve a suitable low face number (< 20.000) to allow importing it into Solid Works 2018®, Blender 2.79b® and its re-mesh function is used (Octree:6; Mode:Smooth). For able-bodied subjects, the socket can be split in half to allow access. After designing the sockets where 3D printed out of PLA using the Ultimaker Extended 2+®.

Figure 3 shows the test setup consisting of a Windows surface book 2 (Intel Core i7-8, 16GB RAM, Windows 10™) as input and control unit and a Matlab® GUI was used to guide the user through experiment E1 to E4. The experiment requests the users to input gender, age and initials firstly, explaining each of the three tests and then letting the user get familiar with the different sensations (tactile and auditory) by pressing a button. The progress in each test is shown in the bottom and resting breaks can be taken by the user at anytime. In the experiment, the setup shown in Figure 3, earplugs (Moldex® Sparkplug® 29dB CL5 Uncorded Earplug) as well as ear muffs (Howard Leight Leightning® Hi-Visibility L3HV 33dB CL5 Headband Earmuff) were used to dampen airborn noise and the experiment was conducted in an audiology booth. The psychometric tests conducted in this paper are analogous to the tests conducted in [9] for the sake of comparability. Three different tests were conducted to estimate three different temporal properties.

**E1:** *Perception Threshold (PT)* The perception threshold was measured in a range of [100 200 400 750 1500 3000 6000] Hz by using a standard two-interval forced-choice (2IFC) threshold procedure, presenting the stimulus and the null stimulus sequential in random order. For each frequency, the null stimulus was chosen as reference stimulus and the target stimulus was varied in amplitude in a stochastic approximation staircase (SAS) manner where the variation was based on the subject's report when perceiving the stimulus. The trial was stopped after 50 iterations and the value for the 51st trial chosen as the perception threshold.
**E2:** *Sensation Discrimination (SD)* The subject was presented with randomly chosen permutations of frequency [100 200 400 750 1500 3000 6000] Hz and amplitude spanning across the whole output range of the transducer in 9 levels. Each permutation was presented twice, and subjects were asked to report the type of sensation (tactile, auditory, tactile and auditory, no sensation). The sensation with the lowest reported threshold at each frequency was chosen as the predominant sensation, in case of equal thresholds both are shown.
**E3:** *Reaction Time (RT)* Three frequencies in the range of tactile (T), auditory+tactile (A+T) and auditory (A), [100 400 1500] Hz respectively, were chosen and the amplitude set to 3 times the threshold obtained for each subject from E1. The goal for the subjects was to respond as quickly as possible by touching the screen on the GUI. A delay of 1 - 4 s was randomly introduced before presenting the stimulation to avoid subjects pre-guessing the response time. A head start was signalled to the subject and the stimulus repeated. Each frequency was presented 30 times and the mean reaction time chosen as the subjects reaction time at the specific frequency.

## III. Results and Discussion

In Figure 4, the results of the three experiments are shown, where S1 is an amputee and all others are able-bodied subjects. The transducers where placed on the elbow of the dominant hand.

### A. Perception Threshold (PT)

Figure 4a shows the perception threshold, where a smaller value means the subject is more sensitive to a stimulation force. In other words, the threshold of the force that can be perceived is lower. The results in Figure 4a show the lowest thresholds and therefore the highest force sensitivity for frequencies lower then 200 Hz. Overall, specifically for frequencies from 100 to 200 Hz, the perception threshold of the amputee, S1, is much smaller than that for the able-bodied subjects. It needs to be stated that the amputee does not wear a prosthesis and has not been using one since early childhood. He uses his stump for all activities in daily life

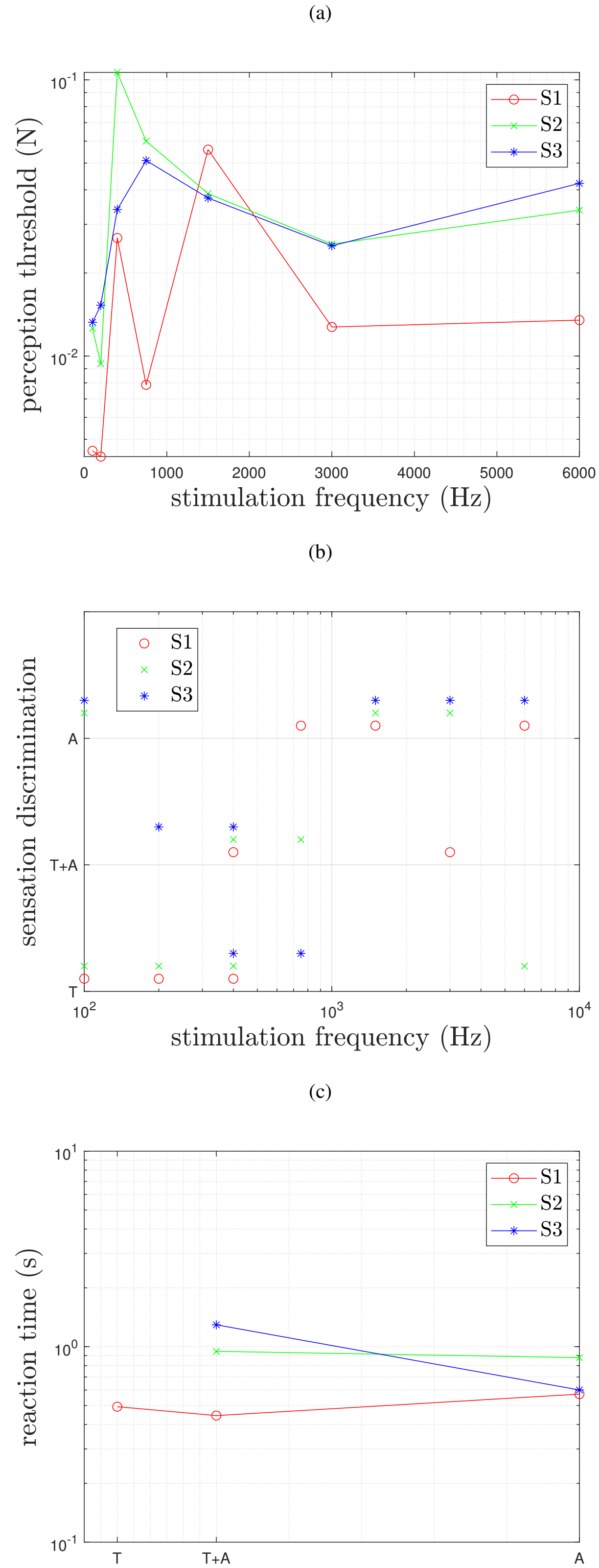


Fig. 4: The results of (a) *Perception Threshold* experiment, (b) *Sensation Discrimination* where reported perception is tactile (T), tactile and auditory (A+T) and auditor (A), (c) *Reaction Time* where [T T+A A] is [100 400 1500] Hz and S1 the amputee.

suggesting an increased sensitivity compared to able-bodied subjects.
Compared to [9] the perception threshold does not increase with increasing the frequency. The perception threshold is not a function of the frequency greater than 200 Hz. Furthermore the maximum perception threshold is up to one magnitude smaller than that observed for the upper limb group in [9].

### B. Sensation Discrimination (SD)

Figure 4b shows the sensation with the lowest reported threshold at each frequency. From 100 to 400 Hz a dominant tactile sensation is present, which is similar to the reported results in invasive bone conduction in [9]. In the range of 400 to 750 Hz both, tactile as well as auditory perception are dominant. Above 750 Hz, dominant auditory perception was reported.

### C. Reaction Time (RT)

Figure 4c shows that the reaction time is comparable for the amputee (S1) with the results obtained in [9] for the upper limb subjects group, having reaction times of 0.49 s (T), 0.44 s (A+T) and 0.57 s (A). Subjects S2 and S3, both able-bodied, reported after the experiment to not have felt the stimulation properly for the lowest frequencies (100 Hz), and therefore stopped randomly after some time. Hence the data is not shown in the plot.

The amputee (S1) reported after the experiment to have perceived the stimulation on different locations on his residual limb during the experiment.

## IV. CONCLUSIONS

The results presented in this study show comparable results for the sensation discrimination. The reaction time for the amputee is similar to the reaction time for the invasive bone conduction reported in [9]. Differing results have been obtained for the frequency dependence of the perception thresholds as well as for able-bodied subjects for reaction time.

The variation between subjects on the perception threshold suggests the need of a personalization of the interface. Similar observation has been made in a preceding study in [11]. Such an adjustment process is known from commercially available sEMG controlled active prostheses.

High sensitivity of perception in lower frequencies means that operating in this range of frequencies requires lower stimulation force from the transducer, allowing more compact transducers and lower power consumption. A smaller transducer also allows for an easier implementation of such into a stump socket and gives the possibility to include multiple transducers. The spatial resolution of such a proposed interface has to be studied, exploring the bony landmarks of the elbow and further extending the capabilities to trans-humeral amputees by using the bony landmarks of the shoulder.

Having a sensory feedback interface, capable of delivering sensations with low stimulation forces over a large frequency range is desirable. A large frequency range increases the bandwidth to deliver feedback information. A low amplitude also decreases airborne sound.

A comparable behaviour for the involvement of auditory as well as tactile perception over the frequency (400 - 750 Hz) has been observed and therefore the involvement of auditory as well as tactile perception within this range is suspected, similar to [9].

Further investigations to apply the proposed feedback interface on a statistical representative number of able-bodied subjects and amputees is necessary. A much smaller perception threshold observed for amputees suggesting an increased sensitivity in amputees who do not wear a prostheses. Further investigations need to take this into consideration and subdivide the amputee group into amputees with and without prostheses.

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