Haptic Foot Interface for Language Communication

Erik Hill*, Hiroyuki Hatano, Masahiro Fujii, and Yu Watanabe
Graduate School of Engineering, Utsunomiya University
7-1-2 Yoto, Utsunomiya, Tochigi, 321-8585 Japan
*e2rzi2k2@gmail.com

ABSTRACT
This paper examines the feasibility of language transmission through a haptic foot interface. The devices tested the placement, timing, and complexity of an array of vibrating electromagnets with the optimal device using an array of ten electromagnets placed under the arch of one foot. Moderate proficiency was reached after only an hour of training at which point the subjects were able to read a short e-mail through the device.

Author Keywords
Haptic interface; feet; HCI; magnets; vibration.

ACM Classification Keywords
H.5.2; H.4.3.

INTRODUCTION
The human foot is a highly sensitive, under stimulated part of our bodies with less use as our societies become more and more sedentary. All of these reasons make the foot a perfect target for a haptic interface device compared with our hands which already have so much to do in our daily lives. As feet are not as sensitive and less trained to localize stimulations, much less usable information can be communicated through them, but this was found to be adequate for language transmission.

Reading through touch has a long history. One of the early notable systems was the French écriture nocturne, or ‘night writing’, which was developed to allow soldiers of Napoleon’s army to read in complete darkness. The system consisted of two columns of six dots each which referred to a 6 x 6 character map but proved too complex to be practical. It however led to the later French system, braille: the most widely used touch-based text system today.

Modern research into haptic devices has also put much effort into technologies for the blind as with Tactile-Vision Sensory Substitution (TVSS) [1] which allows the subject to sense sight through touch. One of the most interesting branches of this research was Bach-y-Rita's device that mapped visual data from a camera to a mouthpiece, allowing subjects to see with their tongues. It was originally developed in the 1960s using direct electrical stimulation to the outer skin; however it was switched to the tongue as the tongue is highly sensitive and saliva is naturally conductive. Because of this, stimulating the tongue only needed 3% of the current that normal skin would [2].

TVSS has also been applied with large electromechanical braille displays which use pressure or vibration to convey visual information, being read either with the hand or the skin of the abdomen of a blind subject [1]. Other haptic technologies for the blind include dynamic Braille displays [3] where the pins of the Braille lettering retract and extend to change the text.

Haptics have been applied in other fields to allow a user to feel a 3-D virtual object [4], feel texture and scalpel resistance in the teleoperation of surgical robotics [5] [6], and experience feedback in flight control systems and video games alike. These systems use vibration and/or pressure through magnetic stimulation of a permanent magnet [7], interaction between a series of levitating high-power electromagnets [6], vibrating motors [4], or mechanical pressure. Whether originating from a controller, a device attached to the hand, or embedded in a touch screen [8], the feedback is almost exclusively directed toward the fingertips or hands. Haptic devices for the feet have been limited to simple nonverbal communication [9] or walking simulation for patient rehabilitation.

THE EARLY PROTOTYPE
The original interface consisted of two slippers with twelve electromagnets fitted atop them. Permanent magnets were attached directly to the foot which allowed enough flexibility in their placement for one interface device to fit a wide range of foot sizes. The top of the foot was chosen rather than the bottom because it was both easier to build a device over the foot rather than under and initial tests showed the skin there to be sensitive enough to localize the vibrations. The magnets 1, 2 and 3 were placed between the toes, magnets 4 and 5 on the side of the foot, and magnet 6 on the center top.

Japanese was chosen as the output language because it mapped more easily to the foot than would English. Although Japanese has 97 characters orthographically, it has only nine consonants, five vowels, and three character modifiers (diacritics). Vowels were mapped to the right foot
and consonants to the other. To make it more intuitive to the user, a consonant-vowel pair would be transmitted as one set, just as it is in Japanese writing. For example the word for mosquito, ‘ka,’ would be transmitted by vibrating the ‘k’ magnet on the left foot along with the ‘a’ magnet on the right at the same time. A ‘shift’ magnet on each foot could precede this to signify a secondary meaning to the magnet, changing ‘ka’ to ‘ma’ (if the left shift were activated), to ‘ke’ (were it the right shift), or ‘me’ (were it both). The voicing diacritic (magnet 4 on the right foot) would change ‘ka’ to ‘ga’ while the labialization diacritic (magnet 5 on the right foot) would change ‘ha’ to ‘pa’. These diacritics are a regular part of the Japanese orthography. Both magnet 4 and 5 being fired would mean the character was orthographically small. The magnets were vibrated in 10 ms pulses because that was found to be the easiest for the users to both feel and localize the sensation. Since the goal of the device was to be moderately usable after only an hour of training, actuation was left long with 800 ms for character keys, 600 ms for shift keys, and 400 ms for diacritics. This meant transmission could take from 800 ms to 1800 ms depending on the character. Originally the shift magnet was actuated at the same time as the character magnet, but having two magnets vibrating on the foot at the same time often was felt as one sensation at a point between the two magnets. To fix this, the actuations were staggered with the shift magnets being fired before the characters. This led to a short increase in time but a high increase in accuracy. For testing, the device output was paused between characters until the user pressed a ‘next character’ button. Firing time could be further reduced after the user became familiar with the patterns of stimulation [10] [11] but was left longer to facilitate training. Accuracy was graded based on character complexity with a single vowel like ‘a’ being worth one point, a compound like ‘ka’ being worth two points, and a compound with a diacritic like ‘ga’ being worth three points. The user was allowed to refer to a sheet with the character mappings during the tests.

Although initial tests were promising, several problems arose with this device. The mapping of the alphabet was logical and easy to understand for the users, but since they were unfamiliar with it before starting the training, it took added effort to learn. Also the mapping required the user to interpret sensations from both feet at the same time which led to a large increase in comprehension time—from under two seconds to interpret a single character magnet to an average of 12 seconds when magnets were fired on both feet at the same time. Staggering the firing of the character magnets could increase speed, but the users would still be very dependent on seeing the character map reference sheet without training significantly longer than an hour.

Another problem was the placement of the magnets. Although sensations on the inner foot were easy to localize, best magnet placement among the toes and atop the foot differed. An ideal position for one user might be highly sensitive but difficult to localize for another user (magnets 2 and 3) or lack adequate sensitivity. Also if the feet became cold during the test, sensitivity was drastically reduced among the extremities (magnets 1, 2, 3 and 4). This was not so much a problem with magnet 5 which was toward the center. Furthermore, since the magnets were attached to the foot and not the device, lots of care had to be taken with foot position so that the magnets didn’t come into contact with the inside of the haptic device or they would lack the space to vibrate properly. Due to the above problems, results were poor for the initial two users. After an hour of training the users averaged only a 76% accuracy with low speed (12 seconds per character) and high cognitive strain. Instead of continuing the trials, the device was redesigned to address the deficiencies.

**THE IMPROVED DEVICE**

The lessons learned from the first device went into the design of the second. The prior model’s character mapping suffered from not being familiar, so the mapping was changed to match a Japanese cellular phone keypad which all users knew quite well. Japanese was kept as the output language to allow better comparisons between the two devices, but a similar mapping could be equally applied to English. An example of the mapping on an English keypad would be to send the message ‘OK,’ by pressing key 6 three times followed by a pause and pressing 5 twice. For the device, the key presses would be replaced by vibrations. The main difference between an English and a Japanese keypad is that for Japanese, one key can represent up to ten characters while English keypads only represent up to four. The new mapping required much less training time as well as allowing all of the magnets to be placed on one foot.
which solved the problem of the user having to interpret signals from both feet at the same time. The array of magnets could be reduced from the 12 of a keypad to 10, with the punctuation and diacritic keys being replaced by 120 ms patterns of vibrations using the other magnets.

The haptic input was still made by permanent magnets being vibrated by electromagnets, but the permanent magnets were fixed to a silicone membrane which was attached to the device under the arch of the foot. This moved the interface to the bottom of the foot which is far more sensitive than the top as well as removing the problem of magnets not vibrating due to being trapped between the foot and the device. Furthermore the center of the foot is much less prone to losing sensitivity should the foot become cold.

The actuation times could be greatly reduced on the new device for three reasons: the increased sensitivity of the bottom of the foot, ‘shift’ magnets were no longer needed reducing one step in the transmission process, and the input was only received through one foot so the user could interpret the sensation faster. One actuation consisted of 10 ms pulses for 200 ms with 100 ms pauses between same-key actuation. Diacritics and punctuation were represented with 120 ms sequences of keys: for example a space was the sequence (2, 5, 8) with 40 ms of vibration at each. The total length of a single character ranges from 200 ms to 2900 ms although it would be rare for a character to be more than 1700 ms. The average length of common characters including diacritics but not including spaces is 850 ms.

EVALUATION
For the first forty-five minutes, the user was allowed to see the input being sent to their foot on the computer screen and could practice blind sends with the researcher verifying the user’s interpretation. After that, the user was given a sheet of paper and told to write the message to be received through the haptic device. They could look at a cellular phone keypad as a reference although this was not needed to interpret the message. It allowed for the user to concentrate more on the haptic stimulations and gave a slight increase in speed but wouldn’t be necessary with more training. The flow of the transmission was controlled with a next-character button. Four short Japanese sentences were tested with an average length of 13 characters. The users could not go back and change the characters they had written down. The testing took fifteen minutes.

RESULTS
With the new device, each character took an average of four seconds to interpret and transcribe, not including the length of the actuation. This was a great increase over the original device (haptic stimulation on both feet) where the user took about twelve seconds to interpret a character on average.

Two factors that contributed to longer character recognition times were the subject’s familiarity with typing on a Japanese cellular phone keypad and the ‘drifting’ of keys. Most users had very high accuracy of the location of the vibration in practice blind sends of a single character after only ten minutes of using the device. However when a magnet was not felt for a while or if the user took a short break between blind reads, it was harder to localize the magnets correctly. This lead to the subjects ‘thinking through’ the sensation to try to place it to an actuator which took extra time. Confusion was more commonly vertical in nature where key pairs such as (1, 4), (6, 9) and (3, 6) were confused more than horizontal pairs such as with (1, 2). One way to increase accuracy was to periodically cycle through all keys so the user could remember their location. This was a request often made by the users between blind practice reads.

Accuracy for the test was just under 90% for a straight interpretation with no corrections. If the subject was allowed to go back over the message and fix what they
thought was wrong, accuracy improved much as often the message could be guessed if first recorded with a good accuracy. Other than the problem of localization drift, users occasionally lost track of how many times an actuator fired. Lapses in concentration rather than difficulty in sensing the vibrations was the main cause. Users often stated after the test that the device took a great deal of concentration, especially after they became unsure of the location of one of the vibrations during a message. Although this level of concentration decreased when the users tested the device on subsequent days, they said they would not feel confident performing another task at the same time unless the message was short or from a limited set of words.

**CONCLUSION AND FUTURE DIRECTIONS**

The device showed that a foot is a viable target for a haptic interface device even with complex input, although having the set of messages include all possible words and sentences might be seen as an upper limit rather than a practical target. Limiting the set to simple sentences or to a preset list of messages would require less training and perhaps a more simplified array of actuators. Even with this constraint, haptic foot interfaces could have applications where the eyes are occupied and hands or ears are not or cannot be fitted with a communication device. These might include vehicle control feedback, rear proximity detection, or system and environment alerts.

It was found that changing the vibrations of a single magnet in the array made it easier to identify since even if the user was unsure of the location, they could recognize it by the distinct feel. This could be applied to all magnets. There are several other changes that might improve the success rate of the device such as spreading the actuator array across more of the foot or using a different mapping of the alphabet. A Morse code style of encoding might also prove to be useful and allow for a simpler actuator array but would have a steep learning curve.

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**REFERENCES**


