

# MoveMe: 3D Haptic Support for a Musical Instrument

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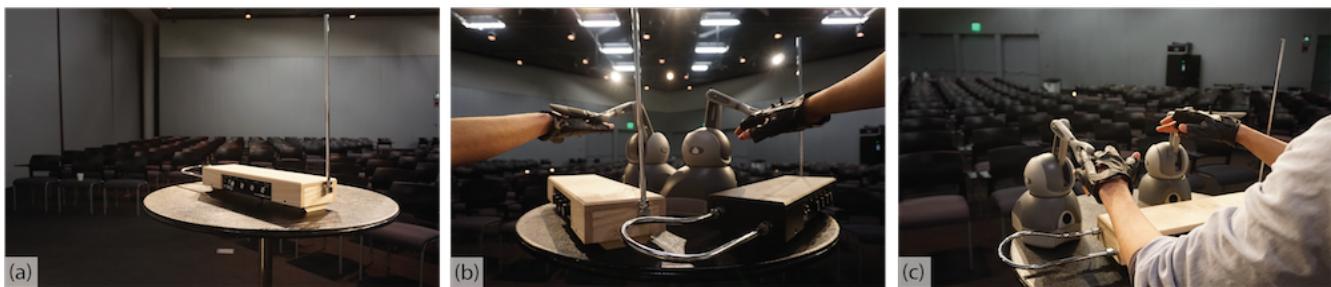


Figure 1 (a) Theremin (b) The system connects an expert and a beginner via two haptic robots.  
(c) An expert can pre-record his/her movements so that a beginner can play it back later as necessary.

## ABSTRACT

Fine motor skills like finger/hand manipulations are essential for playing musical instruments and these skills require a great amount of time and effort to acquire. Researchers have been introducing haptic feedback systems in order to facilitate the process of learning motor skills but little research has expanded the possibility of applying to the field of musical instruments. Hence, we developed a system called “MoveMe” that provides three-dimensional haptic support for playing a musical instrument. The system guides a user’s hands as if someone else was holding their hands to help a beginner play a musical instrument. With the system, an expert can pre-record his/her movements so that a beginner can play it back later as necessary. Alternatively, the system connects an expert and a beginner via two haptic robots and the expert can, in real time, guide and correct the beginner’s movement. In addition to those functionalities, we introduce a new proficiency metric provided by force feedback. A master can evaluate how much a beginner has improved using both audio feedback as well as this new force-based metric. Through the experiments that we conducted, we found that our system is effective in terms of playing a song at a correct speed and rhythm.

## AUTHOR KEYWORDS

Haptic, hand manipulation, music, learning, remote teaching

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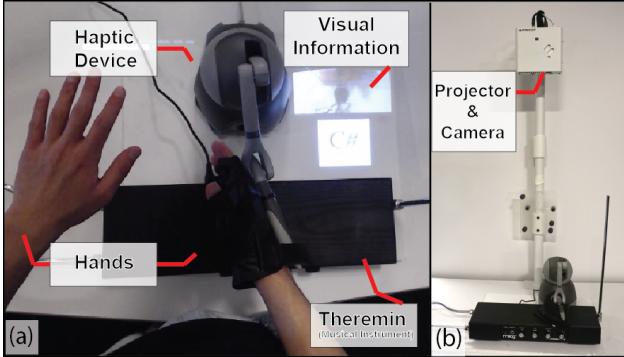
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## INTRODUCTION

Playing musical instruments utilizes kinesthetic learning skills that require a great amount of time and effort to acquire. Kinesthetic haptic interfaces are haptic interfaces that exert controlled forces on the human body to train motor skills, and they have proved to be efficient in teaching skills in such fields as surgery, assembly or rehabilitation [1]. Generally, the motor skills controlled by this type of system are finger- or hand-manipulation. Several research projects have been conducted with these movements in mind, not only for musical instruments, but also for artistic disciplines such as drawing or sculpting [5][6].

In the field of musical instruments, vibration feedback or electrical stimuli to the muscles around the forearm is commonly utilized for manipulating finger movements programmatically [2][3]. Those systems allow users to play melodies with no previous experience in playing a musical instrument. Like the research above, most of the research has been focusing on finger-manipulation, despite the fact that hand manipulation is as important as finger manipulation in playing musical instruments.

Musical instruments have several factors that make it uniquely inappropriate for currently existing projects to be applied to them. For example, playing musical instruments requires continuous movements, unlike object manipulations that can be executed in step-by-step processes. Performing a song relies on playing sets of shifting notes, and the way you shift from one note to another can dramatically change the atmosphere of the song. Additionally, the output from musical instruments is audial, which means timing, rhythm and other real-time properties should be taken into account.



**Figure 2 System Configuration for MoveMe**  
**(a. Top view, b. Front view)**

In this paper, we propose a 3D hand manipulation system called “*MoveMe*” focusing specifically on the use of hand manipulation in playing a musical instrument. (Figure 1,2) With the system, an expert can pre-record his movements so that beginners can play it back later as necessary. Additionally, the system connects an expert and a beginner via two haptic robots and the expert can, in real time, guide and correct the beginner’s movements. We then introduce a new proficiency metric provided by force feedback. A master can evaluate how much a beginner has improved using both audio feedback as well as this new force-based metric.

## RELATED WORK

Here are some several projects that focus on hand manipulation. Also, we look into supporting systems for a musical instrument.

### Hand Manipulation

Providing a physical force is not the only way to support hand manipulations. For decades, augmented reality has been used to provide rich visual contents that support some tasks, including hand manipulations [12]. While not visual, haptic feedback is often used for hand manipulation by stimulating different nerves and receptors in the user’s skin, including free and sensory hair nerves as well as receptors for cold, heat, touch, pressure, and pain [13][14]. Researchers compared those haptic feedback approaches in order to find out the efficiency of each [15][16]. Recent projects include SPIDAR-8, which is a system for implementing direct, two-handed, multi-finger manipulations in a virtual world [7]. Affordance++ stimulates the user’s arm with electricity and allows objects not only to allow the user actuate them but also perform required movements [17].

### Support System for Musical Instruments

Several projects have been conducted in order to enhance instrument learning, in which visual representations are a common approach. One recent project is P.I.A.N.O, an interactive projected augmentation system in which users can see block graphics colored to represent fingering.

Talkegwa et al took a similar approach [4][19]. Xiao developed MirroFugure [8], a system that shows video of full-scaled physical hands shown in situ at the keyboard and Andante [9], a representation of music as animated characters walking along the piano keyboard appearing to play the physical keys with each step. Some systems are even commercially available [10]. Haptic detents provide the augmented interface for the theremin so that the musician can feel the locations of equal tempered pitch, which provide improved accuracy in pitch selection [11].

## SYSTEM CONFIGURATION

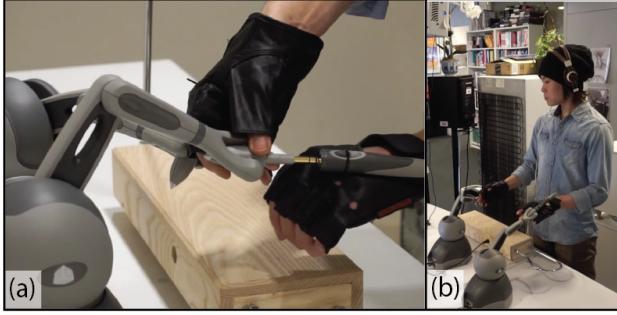
Our system aims to explore the possibility of a haptic support system for playing a musical instrument, specifically focusing on hand manipulation. In order to implement the first proof-of-concept prototype, we chose the theremin, a musical instrument that a musician plays by moving his hands in the air to manipulate an electromagnetic field. Thus, correct hand manipulations are critical in order to make a proper sound. Additionally, as theremins work by producing an electromagnetic field that could get disrupted by the proximity of additional people, a teacher cannot get close to a theremin when teaching a beginner. A haptic device can be utilized in this case, as it minimizes interference with the electromagnetic field. As for haptic feedback, we adopted a physical force feedback that mechanically moves the user’s hands rather than vibro-tactile feedback or electrical muscle stimulation that might be too vague in terms of providing support for hand manipulation.

### Theremin

The theremin is an electrical music instrument which creates a unique sound by detecting user’s hand position. It contains two metal antennas, the distance from one antenna determines the pitch and the distance from other the controls volume.

Theremins emit electromagnetic fields around two antennae and sense the proximity of the user’s hand. Inexperienced players often produce earsplitting blats and squawks as they don’t have any visual cues, such as those they would get from pianos or guitars. More specifically, pianos and guitars have keys and frets, respectively, that provide haptic sensation and each position on the instrument has designated sound. Novices can practice by visually confirming their finger position which helps drive them to perform the correct movements. This is not the case for the theremin as there is no physical contact with the instrument.

A great player must possess a good ear, fine muscle control and ample coordination. Also, as a theremin is affected by ambient temperature or capacitive environments which cause the electronics inside to change, it is hard to achieve the same tuning unless you re-adjust the pitch correction every time you play.



**Figure 3 (a)** User's hand can be easily attached to the device.  
**(b)** Pre-recording a master's movement.

### Phantom Haptic

We used a Phantom haptic interface by SensAble Technologies [18]. The device includes a robot arm with a stylus pen connected to its end. The device measures hand movement caused by pivoting at wrist by providing the position of the stylus in x, y, and z coordinates. It is capable of measuring the stylus position with a resolution of less than 0.005mm at a speed of 1kHz. The workspace is 60 width x 120 height x 70 depth mm. A user of this system wears gloves attached to the stylus pen of the Phantom Device and the stylus pen can be easily attached to the device. (Figure 3). We aimed to design this in such a way that users do not have to spend a long time to learn how to use this system, so the system's movements closely resemble natural hand motions.

### Force Feedback

The system gets inputs of the current position of the device ( $C_i$ ) and a target position ( $T_i$ ) at time  $i$  ( $i = 0..n$ ) in 1kHz. At N times, the system calculates difference ( $D_i$ ) between  $C_i$  and  $T_i$ .

$$C_i = \{x_i, y_i, z_i\} \quad (i = 0..n) \quad (1)$$

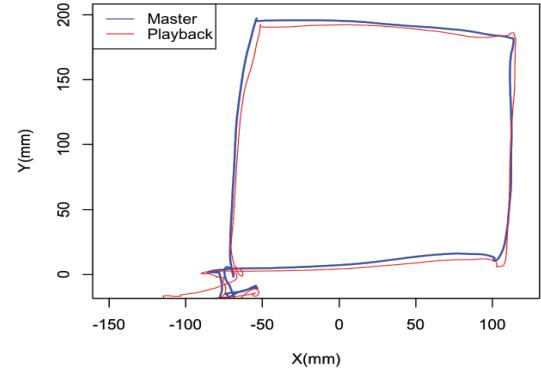
$$T_i = \{x_i, y_i, z_i\} \quad (i = 0..n) \quad (2)$$

$$D_i = T_i - C_i \quad (3)$$

Force feedback is calculated using a standard force spring model and a user can define the value of multiplier setting the parameters in the external GUI. The calculated force is used as parameters to move motors of the device.

$$F_i = S \times D_i \quad (4)$$

Figure 4 shows the hand movements in Cartesian coordinates (x and y). We first recorded a hand movement of a user drawing a square in two-dimensional mid-air space and this movement set as target positions. Then we played it back so that another user can draw the same square feeling the haptic feedback calculated with the equation mentioned above. The maximum error was 4.43(mm).

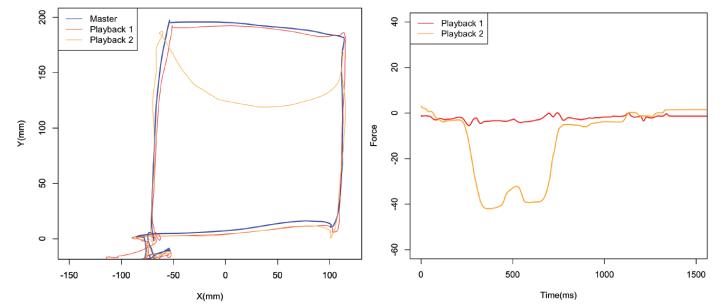


**Figure 4 Accuracy evaluation of the playback**

We then measured the maximum force in three-dimension. The result was 1.3N, 1.48N, 1.86N for x, y, and z in Cartesian coordinates respectively. This is the necessary force that users need when they want to reject the support from the master at the maximum. In other words, the users can override the feedback from the master if necessary.

### Force-Based Proficiency Metric

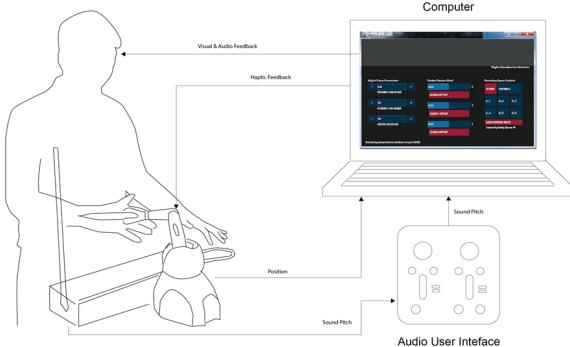
The more similarly the beginner plays to the master, the less force feedback the beginner feels because he no longer requires adjustment by the master. By looking at the change in force feedback, we can create a numerical learning metric that shows how correctly the beginner is playing.



**Figure 5 Force feedback can be used as proficiency metric**

Figure 5 shows the same movements as the accuracy test above. But we intentionally added one movement that rejected the guide. We can see that the extra force is provided in order to get the beginner's movement to the correct positions.

By combining audial feedback, we can make it more efficient for a master to teach a beginner. This can also be used by a beginner to see, numerically, how much he has improved.



**Figure 6 System Configuration of Record-Playback System**

## FUNCTIONALITY

With the implementation above, we created two different modes the system: Record-Playback and Remote-Teaching.

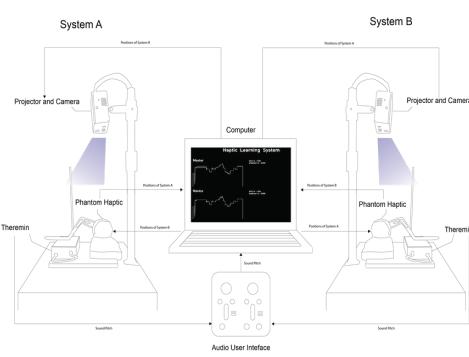
### Record-Playback System

An important aspect of musical learning is practice and, by extension, repetition. The haptic system we developed allows a teacher to record his movements so that a student can playback the sequence as many times as he might desire and learn from a consistent set of motions. (Figure 6) By placing the coordinates of the device in a queue every millisecond, the motions of the master can be replayed with high fidelity at a later point in time.

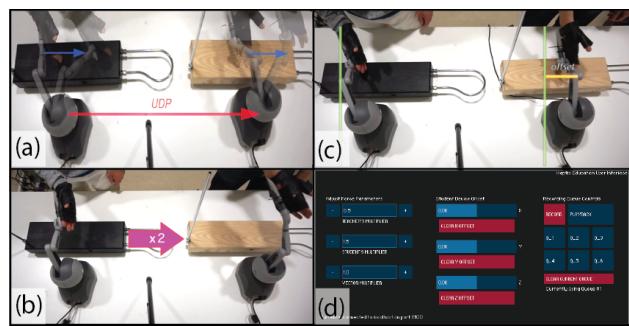
Given the same type of device, the same sequence can be replayed on every device, thus expanding the lesson setting from an individual session to one closer resembling a classroom. Alternatively, our interface allows the teacher to record different sets of motions on different devices, which reincorporates the ideas behind one-on-one teaching into the wider classroom.

### Remote-Teaching System

The two devices can communicate with each other and an external graphical user interface over a UDP connection. (Figure 7) Over this connection, the two devices can synchronize their movements and positions and this synchronicity can be adjusted according to parameters set in the external GUI. (Figure 8) Our system supports bidirectional force feedback. In other words, not only can a beginner feel what a master is doing, but the master can also feel what the beginner is doing. By changing the value of multiplier, the beginner may also change how much he wants to feel the feedback from the master.



**Figure 7 System Configuration of Remote-Teaching System**



**Figure 8 (a) Two devices are synchronized over UDP connection (b) Scaling functionality (c) Offset functionality (d) Graphical User Interface of the system.**

### Remote Teaching in Real-Time

One device guides the movements of the other and force parameters can be adjusted so that the guided device feels the instructions of the teaching device more or less strongly, thus allowing the student less or more freedom (respectively) to make his own motions. Conversely, the guided device's parameters may be adjusted to allow the teacher to feel more or less of the student's movements.

By adjusting the position scale between the two devices, the motions of one can reflect the amplified motions of the other; for example, moving a device one inch to the right could make the other move two inches to the right. This allows a student the chance to appreciate even subtle movements by first feeling them in an amplified manner.

The position of the devices is given in three-dimensional Cartesian space. By implementing the ability to offset one device's motion a set quantity (in terms of x, y, and z) from the other, a master can adjust a pitch of the other device in case the tunings of two devices are different. In case of theremin, pitches might be different even at the same coordinates due to the surrounding environment that affects the electromagnetic field.

Furthermore, with the offset functionality, the two devices can become more than the sum of their parts. In the case of the theremin, offsetting one device from the other can

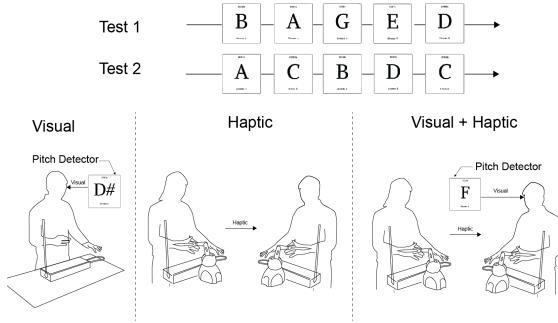
allow the two to play in harmony, thus adding another aspect—that of collaboration—to a student’s education.

## EXPERIMENTS

In this section, we explored the possibility of using haptic feedback for a musical instrument.

### Record-Playback

In 2002 work by Feygin looked at learning motor skills with haptic feedback, and they found that visual training was better for teaching the trajectory shape whereas temporal aspects of the task were more effectively learned from haptic guidance. [20] Therefore in this experiment, we compare the effectiveness of haptic feedback to visual feedback, as applied to playing a musical instrument. The participants of this experiment consist of 3 males (21, 25 and 32 years old) and 2 females (20 and 25 years old). None of the participants play musical instruments on a daily basis nor have they taken any serious lessons of musical instruments. They were asked to play different notes in series and they received three different feedbacks during the experiments: visual, haptic and visual-haptic (Figure 9). Haptic feedback is provided by a master's hand movements. We randomized the order of the feedback depending on the participants in order to get rid of “getting used to” results.

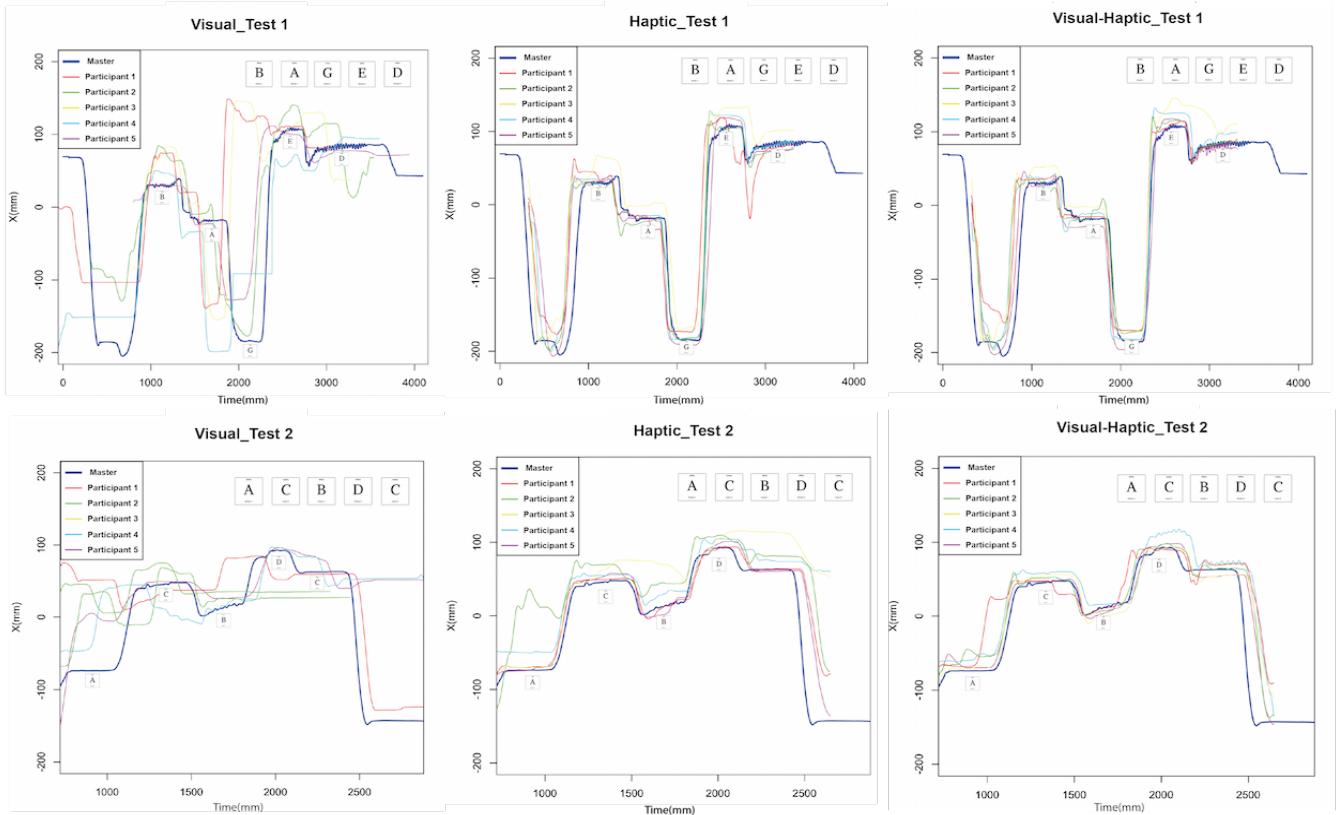


**Figure 9 Comparison of visual, haptic and visual-haptic**

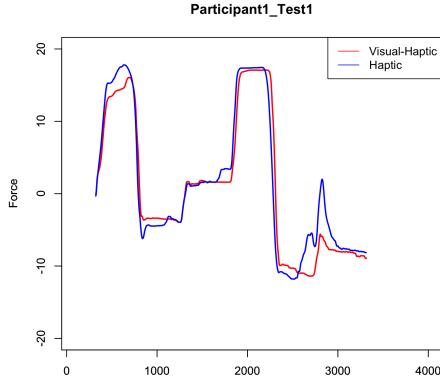
For visual feedback, we used a pitch detector, which is commonly used for practicing musical instruments. The pitch detector could detect 12 different pitches (C note to B note) as the participants played and the note was projected on a display as shown in Figure 9. The experiment was conducted twice and we recorded novice's hand movement in x, y, z and compared the result with the master's hand movement.

### Result

Figure 10 shows the result of experiments with visual, haptic and visual-haptic feedback respectively for each participant with the comparison of the master movements in x coordinate.



**Figure 10 The tests done with the haptic feedback (including visual-haptic) resulted in superior results compared to the tests done with only visual feedback.**

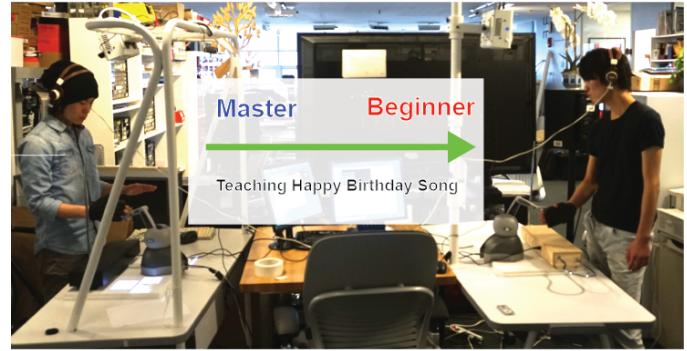


**Figure 11 Force feedback that the participant 1 received during the experiment Test 1**

The tests done with the haptic feedback (including visual-haptic) resulted in superior to the tests done with only visual feedback. In terms of hitting the correct notes, the tests done with visual also resulted correctly. Interestingly, some participants said that they didn't know if they should move their hands to the right or left, and that made them take several seconds until they hit the correct note. Even though they could hit the correct notes, the timing and speed deviated from the original tune, whereas the haptic feedback allowed users to copy all of the movements, such as shifting from one note to another, correctly. This is extremely important when playing a musical instrument as the way one shifts between notes can dictate a wide variety of sounds. The visual-haptic support resulted slightly better than the haptic-only support. Figure 11 shows the force feedback that the participant1 (female participant) was getting during the experiment Test1 with the visual-haptic support and the visual-only support. Force feedback was provided when she shifted from one note to another. When she got closer to the point, we can see that she felt slightly stronger adjustment at the first and the last notes when guided by the haptic-only system. This metric makes it possible to evaluate their improvement in hand manipulations.

#### Remote-Teaching

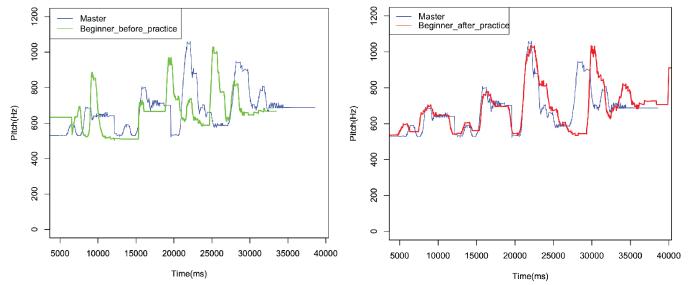
In addition to the experiment above, we asked a master with 3 years of experience in playing a theremin to play "Happy Birthday Song". (Figure 12) First we asked a beginner (a 25 year old who had never played the theremin before) to practice the song for 20 minutes. We recorded his hand movements in Cartesian coordinates. Second, the master taught the beginner via the remotely connected haptic devices and we gave them another 20 minutes of practice. We compared the hand movements of before and after practicing. We conducted these two experiments in different days (the second experiment was conducted a week later of the first experiment day) in order to make it clear whether the training itself had an effect or whether participants got more practice in a given condition.



**Figure 12 A master teaches a beginner how to play a song**

#### Result

Figure 13 shows the hand movements of the beginner playing the song after 20 minutes of self-practicing and with the Remote-Teaching system. When he first started practicing, he tended to ignore the visual tuning display and kept playing the song with incorrect pitches.



**Figure 13 Remote-Teaching system helped a beginner learn effectively**

After a few minutes, he began to use feedback from the pitch detector. Repeating this routine ended up being inefficient since the sound feedback he received sometimes contained incorrect sounds. After 20 minutes of practice, the sounds he created remained mismatched to the original melody. The tempo and rhythm were likewise different from the master's song.

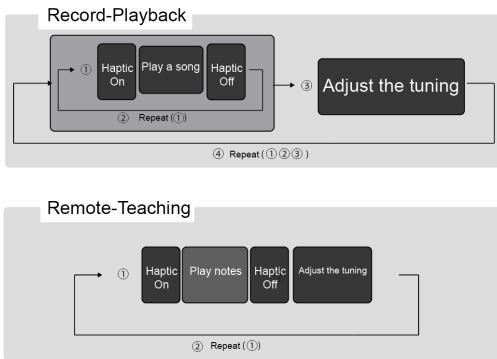
On the other hand, in Remote-Teaching system, the master kept asking the beginner to adjust the tuning and hit the first note correctly (in the case of "Happy Birthday Song", the first note is C) throughout the whole experiment. This allowed the beginner to get a correct feedback and he modification of the movements were made notes by notes. As a result, the beginner could play the similar pitch with more correct rhythm.

## MOVEME AS A LEARNING SYSTEM

The system is capable of letting a user perform a song, even for the first time trial. Self-achievement is always a pleasure and thus encourages a beginner to continue practicing.

It is important to mention that our system is very effective when it comes to practicing a theremin, as pitch is created by changing the emitted electromagnetic field with one's hand. Thus, it is not appropriate for a master to step in since it might affect the field generated by the instrument. With our system, the master can teach remotely or the beginner can use the pre-recorded movements of the master to play.

As to “learning” in general, we can design a learning routine using *MoveMe*. (Figure 14) We assume that the Record-Playback mode can allow a user to learn how he should move his hand. Through the experiment, we found that people with no experience in playing a musical instrument cannot tell whether they should move their hand to right or left in order to shift from one note to another. This functionality would help people learn in what direction and roughly how far they should move their hand. We also found that people tend to ignore other forms of feedback when they receive guidance from the haptic device. This is possibly because it is too hard for users to pay attention to both haptic and audial feedback. As a future work, we plan to make our system more interactive so that the system can give them information that would encourage them to adjust the tuning.



**Figure 14** Design of learning routing using *MoveMe*

We believe that the Remote-Teaching can be effective for learning musical instruments. This mode is an extension of the conventional “hand in hand” system. In our experiment, the master kept asking the beginner to adjust the tuning and hit each note throughout the whole experiment. Every time the beginner hit next note, the master adjusted with sending a subtle haptic feedback. In this way, a beginner can get correct audio feedback as well as how he should move his hands.

## DISCUSSION AND FUTURE WORK

### Technical limitations

In order to pursue the scalability of our system, we need to take into account some technical limitations that we aim to address as we explore further research.

### Comparison with other types of feedback

As the first prototype, our system adopted Phantom Haptic, which is only capable of providing x, y, and z positions and cannot provide pitch, roll and yaw parameters. In this paper, we found out that our system is effective in terms of hand manipulation for shifting from one point to another. This appears to be an advantage compared to other types of feedback such as vibro-tactile feedback, which does not provide such clear instructions in terms of direction. In the future, we would like to explore subtlety in hand movements including rotation angles and conduct further experiments to compare other types of feedback in several conditions.

### Connectivity between two haptic devices

Our system allows a master to teach a beginner remotely via haptic devices. We adopted UDP protocol in localhost and we didn't find any issues in terms of latency. However, in real-world applications where the connection would take place over other network areas we would likely have to take into account delays in connectivity. Considering the fact playing musical instruments requires a real-time feedback, this should be explored in detail.

### Other Musical instruments

In this paper, we explored the possibility of using our system for 3D hand manipulation relevant to musical instruments. By combining our system with finger manipulation projects, we can expand the applications of the system. For example, with a finger manipulation system and a position detection system like motion capture cameras, the combined system can teach users how to properly hold a string on guitar or violin and our system can teach how to stroke. As a future work, we would like to improve our system and explore the possibility of applying our research to other musical instruments.

## CONCLUSION

We developed a system called “*MoveMe*” that provides three-dimensional haptic support for playing a musical instrument. The system has two different modes, Record-Playback and Remote-Teaching mode. In the Record-Playback mode, an expert can pre-record his movements so that beginners can play it back later as necessary. Remote-Teaching mode connects an expert and a beginner via two haptic robots and the expert can, in real time, guide and correct the beginner's movement. By looking at the change in force feedback, users can tell how much they have improved in via a numerical metric which we refer to as “Force-Based Proficiency Metric”.

The master can use this metric in order to know how much the beginner has improved. In the experiments, we found out that our system can help beginner to play a song at the correct speed and rhythm. When a beginner was connected with a master through this system, the beginner could practice a song more effectively than he could by practicing without the system. We then discussed the possibility of using our system as a learning method, which was followed by a description of the technical limitations. Further research is to be conducted in order to explore the full potential of the system.

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