Good vibrations: Guiding body movements with vibrotactile feedback

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Good Vibrations: Guiding Body Movements with Vibrotactile Feedback

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ABSTRACT
We describe the ongoing development of a system to support the teaching of good posture and bowing technique to novice violin players. Using an inertial motion capture system we can track in real-time a player's bowing action and how it deviates from a target trajectory set by their music teacher. The system provides real-time vibrotactile feedback on the correctness of the student's posture and bowing action. We present the findings of an initial study that shows that vibrotactile feedback can guide arm movements in one and two dimension pointing tasks. The advantages of vibrotactile feedback for teaching basic bowing technique to novice violin players are that it does not place demands on the students' visual and auditory systems which are already heavily involved in the activity of music making, and is understood with little training.

Categories and Subject Descriptors
H.4 [**Information Systems Applications**]: Miscellaneous.

General Terms
Experimentation.

Keywords
Violin bowing; motion capture; vibrotactile feedback; teaching system

1. INTRODUCTION
As part of the e-sense project (http://www.esenseproject.org) we are building novel augmentation devices to explore sensory, bodily and cognitive extension [3]. Our research breaks away from desktop- and GUI-based styles of interacting with technologies, and focuses on the development of devices that facilitate more physical forms of interaction. We have developed a wearable vibrotactile array and initial experiments have demonstrated that vibrations generated by this device can guide behaviour. For example, the system has been used as part of a minimal tactile vision sensory substitution (TVSS) system that maps an image captured by a webcam (either fixed or head-mounted) into vibrotactile stimulation. When blindfolded participants wear the array on their abdomen, they quickly learn how to track and bat balls rolled towards them along a table (see [4] for more details).

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In this paper we describe the ongoing development of a system to support the teaching of good posture and bowing technique to novice violin players. We use an inertial motion capture system to track the bowing action of the musicians and use vibrotactile feedback to guide their movement along the correct trajectory.

In Section 2 we discuss our motivation for the development of a system to support violin teachers and students, using novel technologies that are physically engaging. In Sections 3 and 4 we highlight the challenges involved in learning and teaching good violin bowing technique, and discuss how we seek to develop a form of embodied learning in which the pupil actually experiences the complex dynamic arm movement that is required for bowing. Section 5 focuses on the motion capture component of our system, and we explain our method for recording a desired bowing trajectory which can then be used as a reference for feedback. We give details of an initial user study with young violinists and their teachers and show an example of actual bowing and how this can be compared to the desired bowing trajectory as set by the teacher. Section 6 describes the development of the feedback component of our system. During training, we will inform the musicians about how their bowing arm movement deviates from the target trajectory using vibrotactile feedback. We present some initial studies that show how vibrotactile feedback can effectively guide arm movements in one and two dimensions and outline how we plan to extend this technique to guide three dimensional bowing movements. Finally, we describe the challenges involved in integrating the existing motion capture and feedback components into a real-time training system.

2. MOTIVATION
A general motivation for our research is that health benefits and a sense of well being result from an increased awareness of body posture and movement. In this study we focus on children learning to play the violin: an activity during which they need to become aware of their precise physical movements and posture in order to learn how to play the instrument.

Advances in technologies for analyzing movement and performance are increasingly applied in sports training, for example, golf, snowboarding and swimming [5, 6, 16, 17]. These technologies have, to a lesser degree, also been used in dance and music science [7] and where used they have tended to focus on expert rather than novice players.

Learning to play the violin requires the development of a range of different skills. Good posture and correctly holding the violin form a fundamental basis of playing technique. Furthermore, the production of a good tone requires a high degree of control of the movements of the bow. During music lessons, teachers demonstrate the correct posture and bowing. However, most novice players will have less than one hour contact time per week with their teacher – the majority of their learning time consists of practicing alone. In the absence of a teacher to guide them, there is a potential danger that novice students play with an inferior technique which is then reinforced through repetition: the more they practice, the more difficult it is for their teacher to correct their playing at the next lesson.

Our goal is therefore to develop technology-based methods to assist novice violin players during their practicing, with the aim of making it more effective and rewarding. Our methods should be considered as complementary to their regular music lessons.

In particular, we are exploring the combination of motion capture technologies and vibrotactile feedback. Motion capture is suitable for measuring instrumental gestures in violin performance. Vibrotactile feedback has some clear advantages over visual and auditory feedback in the context of music performance. Auditory feedback is likely to interfere with the sound produced by the instrument, whereas visual feedback might disrupt other visual tasks, such as reading the score.

3. THE CHALLENGE OF LEARNING BOWING

Bowing action is a complex motor skill that requires the coordination of a number of degrees of freedom in the shoulder, elbow, wrist and hand. A particular difficulty of playing string instruments lies in the sound generation process, which takes place due to the frictional interaction between the bow and the string. A good, regular string vibration (Helmholtz motion) requires a refined coordination of bow velocity, bow force (normal force exerted by the bow on the string) and bow-bridge distance [13]. The player has many degrees of freedom at hand to control the course of the bow and to influence the contact mechanics between the bow and the string. The angle of the bow with the string forms an important factor therein and should therefore be under the control of the player [14]. Research by Konczak and colleagues has shown that novice players require in excess of 700 practice hours in order to master the basic motor skills for bowing [8].

In our study we focus on the particular issue of *straight bowing* in long bow strokes, where the bow remains perpendicular to the strings. Straight bowing is a basic skill that novice players need to accomplish, and forms an important component in learning how to *control* the bow. It should, however, be noted that expert players often exhibit subtle and systematic deviations from straight bowing during expressive performance, and it has been shown that skewness of the bow has an important control function [14].

4. THE CHALLENGE OF TEACHING BOWING

Novice violin players traditionally learn how to hold their violin and bow correctly by: i) observing and imitating their teacher's actions; and ii) listening to verbal feedback from their teacher. Sometimes a mirror is used so that students can watch their own bowing action and posture.

Learning by observation and imitation is challenging for novice players for a number of reasons: i) they often do not know what it is they are looking for; ii) they don't know how to translate what they see into their own body movements. It is very difficult for the teacher to give verbal feedback in the midst of a dynamic bowing action and so generally comments are made after the movement is completed.

In discussions with violin teachers we became aware of a number of additional strategies that are used to teach straight bowing:

i) Bowing through a cardboard tube, such as found in the middle of a roll of kitchen paper. The teacher holds this tube at a straight angle to the strings. The challenge for the pupil is then to bow through this tube without touching its sides. The tube helps to focus the pupil's awareness of the straight path of the bow, and allows them to experience the complex physical movement of the arm.

ii) Passive bowing, where the pupil holds the bow keeping the right arm relaxed, while the teacher guides the bowing movement.

iii) Following the bow with the right hand. In this exercise the teacher places the tip of the bow on the string, keeping it at a straight angle. The bow itself remains stationary during this exercise, and the pupil moves the right hand along the bow, thus performing the type of arm movement required for proper bowing.

These exercises provide the pupil with physical experiences of the correct bowing movement required for straight bowing, even if only briefly or passively (as in the second example, where the teacher guides the movement). It is these moments of embodied learning that we aim to emulate and automate in our system, with the added benefit that it will provide real-time feedback to a student while they are actively performing their actual bowing action.

5. MOTION CAPTURE SYSTEMS

The development of motion capture techniques in the last decade offer new possibilities for the study of bowed-string instrument performance. A variety of systems have been successfully used to measure bowing gestures, using sensors, motion capture systems (optical, as well as magnetic field tracking) or combinations of the two [2, 10, 15, 18].

For our system we used an IGS-190-M mobile motion capture system from Animazoo [1] (Figure 1). This system consists of small inertial measurement units (a combination of three-axis accelerometers, gyroscopes and a magnetometer), suitable for measuring 3D orientation. The sensors are attached to a lycra body suit and the data are transmitted by a wireless processing unit to a receiver connected to a computer.

The advantage of this system is that it is highly mobile and convenient to carry around, and it can therefore be used in settings familiar to the novice players we are working with. The

Figure 1. Tracking the bowing action of a young violin player who is wearing the Animazoo IGS-90-M motion tracking system. The movement of her bowing arm and the position of the violin are tracked using 6 inertial measurement units. The motion capture data are transmitted wirelessly to a

system requires only a few minutes to set up, and provides data that is sufficiently accurate for our purposes.

5.1 Pilot Studies and Findings

We performed a pilot study with three young violin pupils in the presence of their violin teachers, using the motion capture system. For each student we determined the reference bowing trajectory for each string, using the passive bowing and the "follow the bow" exercises as described above under assistance of the teachers. Also the pose of the violin during the exercises was recorded as a reference for the hold of the violin. It should be noted that the reference bowing trajectories are individual, depending on the build of the player and the way she/he holds the violin. The recorded data were used to construct a line, which can then be used as a reference for the pupils' actual bowing without the assistance of the teacher.

The principle of the bowing assessment method is illustrated in Figures 2 and 3, which show a typical example of the bowing movement of a pupil. The reference path obtained in the calibration trial is indicated by a dotted line. It can be seen from the top view (Figure 2) that the bow stroke is reasonably straight,

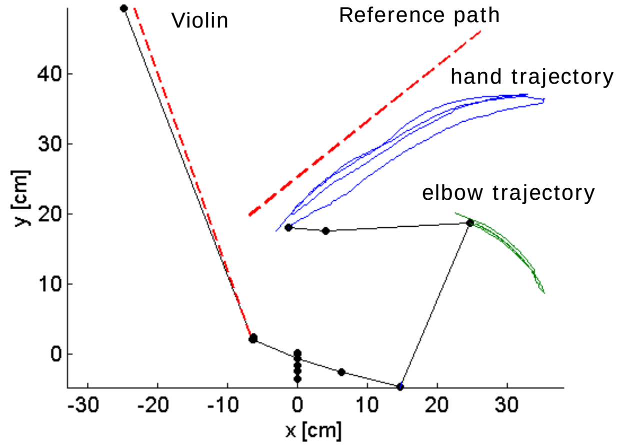

Figure 2: Illustration of bow strokes performed by a novice, showing the bowing trajectory as seen from above. The reference bowing path and the reference position of the violin are indicated by dotted lines.

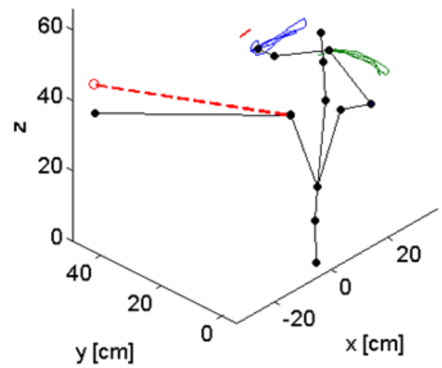

Figure 3. Illustration of bow strokes performed by a novice. The side view clearly shows that the violin position was lowered compared to the reference position.

but shows a stronger deviation when approaching the tip. Furthermore, the bowing trajectory shows a persistent offset, which might indicate that she was bowing too close to the bridge.

The side view (Figure 3) reveals that the violin had dropped compared to the reference position (indicated by a dotted line). This might also have confounded the bowing path, which was in this case not adapted to the orientation of the violin. The appropriate feedback would in this case be to raise the violin and correct the bow movement when approaching the tip.

6. VIBROTACTILE FEEDBACK TO GUIDE MOVEMENT

Our work is related to that of Förster [6], Spelmezan [16], and their colleagues, who explored the use of tactile motion instructions for guiding physical activities, respectively swimming and snowboarding. In these activities auditory feedback is usually not an option: the environment is either too noisy (the presence of water combined with the physical activity of swimming [6]); or the subject's auditory channel is already occupied by listening out for fellow snowboarders approaching from behind or to judge the performance (by the sound of the board on the snow) [16]. Under these circumstances vibrotactile provides a good alternative.

Spelmezan and colleagues [16] conducted a series of experiments to test whether vibrotactile instructions could be used to give real-time feedback to snowboarders.

In the first experiment, vibrating motors were placed on various parts of the body (knees, thighs, arms, chest), and participants were asked to assign meaning to a series of tactile instructions. Some instructions consisted of several vibrations from one motor, while there were also instructions with directional patterns, where three motors are placed in a line, and pulsate one after the other. They reported a 'push-pull' division among the respondents - some respondents interpreted a vibration as a warning signal, and intuitively moved away from the vibration; others felt that they should seek to intensify the vibration.

In the second experiment, meaning was already ascribed to the tactile instructions, and participants were asked to react to the instructions using a Nintendo Wii-Fit balance board for slalom snowboarding. Instructions were set up using the push metaphor, meaning that a vibration on the right side should be interpreted as an instruction to lean to the left. Participants were asked to say aloud which instruction they felt they received, and then to perform the action. This experiment was about testing whether participants could learn the instructions, and could interpret them accurately during physical activity. The experiment confirmed both, and in particular that even though participants experienced physical and cognitive load while using the balance board, they were still able to correctly identify the instructions. The only thing that participants seemed to struggle with was translating the experienced tactile instructions into speech before performing the movements.

In the third experiment snowboarders (with varying degrees of expertise) were asked to board down an actual slope, while responding to instructions coming from the instructor standing at the bottom of the slope. The instructor could communicate to the boarders by sending signals. For example, an instructor could press the 'lean left' button on her mobile phone if she noticed that the boarder was leaning too much towards the right. Pressing this button would cause a vibration on the right side of the boarder's upper body, which would be interpreted as 'being pushed' towards the left, and thus making the boarder lean to left. Boarders had to say out aloud the perceived instruction (whether the instruction was given in auditory or tactile form), and the response time to tactile instructions was compared with response time to auditory commands. The finding was that the response time to tactile instructions was faster than to auditory instructions.

For musicians, listening forms an integral part of music making and interference in that listening process is likely to be distracting. However, in their study of the augmented mirror for violinists Larkin and colleagues [9] provide auditory feedback on bowing techniques in the form of short 'beeping sounds' in preference to visual feedback. They found there was considerable cognitive overload for processing complex visual feedback, particularly since players were already occupied with reading musical scores.

7. INITIAL STUDIES – GUIDING MOVEMENTS IN 1 AND 2 DIMENSIONS

In order to obtain a first indication of the usefulness of vibrotactile feedback for the guidance of bowing trajectories in 3D, we carried out two exploratory studies to see how effectively vibrotactile feedback could guide subjects' arm movements in one and two dimensions. The first task involved moving to a target on a line and the second to a target on the plane. We also wanted to investigate whether our target group (8-12 year olds) finds vibrotactile feedback disruptive or uncomfortable.

We used 10 mm shaftless DC motor [11], commonly used in mobile phones, to provide vibrotactile feedback during these studies. Each motor was driven by an Arduino microcontroller pulse width modulation (PWM) channel. By varying the PWM signal it was possible to control the intensity of vibration, although frequency and amplitude cannot be separately adjusted. We chose these motors as they had been successfully as part of the TVSS system described above [4]. These motors can be updated at least 10 times per second.

Earlier pilot studies had indicated that two vibration motors, located on opposite sides of the wrist, could effectively guide hand movements in one dimension if the feedback intensity was directly proportional to the distance of the hand from the target. The feedback decreased to zero when the hand was over the target, giving users a clear cue that their hand was in the correct location. It did not matter whether the feedback 'pushed' the hand (that is, the motor farthest from the target was activated and the other was switched off) or 'pulled' the hand (that is, the motor closest to the target was active and the other was off). The participants showed a clear preference for a decreasing vibration intensity when approaching the target, as opposed to an increasing intensity when approaching the target.

In the current study we used this 'opposing motor pair' set up to provide 'pushing' vibrotactile feedback in the one dimensional task. In the two dimensional task one of the motors indicated the left/right (x coordinate) distance from the target, and the other the up/down (y coordinate) distance. In this set up, in contrast to the one dimensional task, both motors could be active at the same time.

7.1 Experimental Setup

The experimental set up was the same for both studies (Fig. 4). Subjects stand in front of a computer display where they see a mirror image of themselves captured by a webcam. In the centre of the display is a circle which indicates the starting point of all movements. The subject's hand is covered by a coloured glove allowing the hand to be easily tracked with the webcam and computer vision software. A laptop runs the software and communicates via a USB connection with the Arduino microcontroller to drive the motors on the subject's wrist.

In an initial calibration phase, the subject moves the gloved hand to different locations, and the system stores these as target positions. In the one dimensional task the targets only vary in height (y coordinate); in the two dimensional task the targets vary in both their x and y coordinates. In each task subjects stores 4 targets in the calibration phase.

During the testing phase, each target is presented once under different conditions and the system measures the accuracy of the

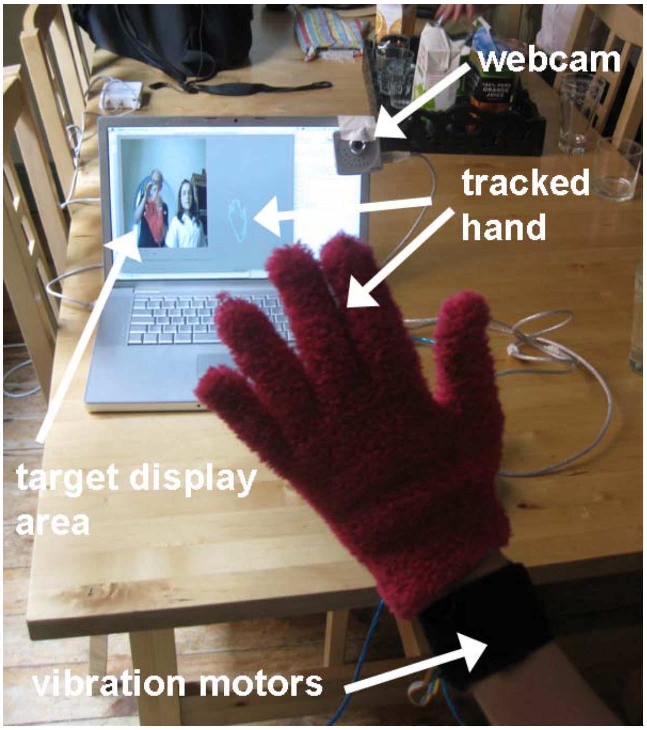

Figure 4. The experimental set up for testing whether two vibration motors could guide arm movements in one and two dimensions. The subjects wear a coloured glove on their moving hand that is tracked using a webcam and computer vision software. Subjects position their hand at a central starting point on the display area and then have to move their hand as quickly as possible to a target location. In some conditions the target position is shown with a brief visual cue. Vibrotactile feedback from two vibration motors provides information about the hand's proximity to the target in some of the test conditions.

subject's movement and how long the movement takes. There are three different conditions:

i) Visual-only - the target appears on the display as a green circle for 1 second and then disappears. The subjects then have to move their hand as quickly as possible to the target location and indicate vocally when they think they have reached it.

ii) Visual + vibrotactile - subjects position their hand at the starting position and see the location of the target for 1 second on the display. When the visual cue disappears they move as quickly as possible towards the target while also receiving vibrotactile feedback that indicates how far they are from the target position.

iii) Vibrotactile-only - subjects position their hand at the starting circle but do not see the visual location of the target, having to rely entirely on vibrotactile feedback to move to the target.

8. DISCUSSION

The analyses showed that in the one-dimensional task, there was no significant difference between the three conditions in accuracy. It was, however, found that in the vibrotactile-only condition it took a longer time to reach the target. This is explained by the fact that in the visual-only and visual + vibrotactile conditions, subjects are able to perform an initial ballistic action followed by a corrective phase (Fitts' law), whereas the tactile-only condition is entirely characterised by closed-loop behaviour, where subjects continuously adjust their movement on the basis of the vibrotactile feedback. A similar time effect was found in the two-dimensional task. Furthermore, the vibrotactile-only condition showed a lower accuracy compared to the other conditions.

None of the subjects reported discomfort and our target group (8-12 year olds) actually found the tasks engaging and 'game-like'. The subjects generally found the 'pushing' vibrotactile feedback intuitive in the one dimensional task and were able to use it straight away to guide their movements. Most subjects needed a few trials to learn how to interpret the feedback in the two dimensional task.

The accuracy results from the one dimensional task show that vibrotactile feedback, presented using an opposing pair of motors that 'push' the hand, is as effective at guiding arm movement to a location as a visual cue that is held in short term memory. The results from the two dimensional task show that if two closely located motors provide distance signals at the same time, then the vibrotactile feedback is not as effective at guiding movement as a visual cue in short term memory. The simultaneous feedback appears to confuse the subjects, but with more training they may learn how to use this type of feedback effectively. Both tasks show that closed-loop movements towards a target are slower than ballistic movements.

9. FUTURE WORK

Building on the initial studies reported in this paper, we will continue and put together the two components of our system in order to have an integrated teaching system delivering real time vibrotactile feedback based on players' bowing actions tracked through the motion capture component. In doing so we will explore the following issues:

1) Collision versus Pushing

In our current study we used the concept of 'feeling no feedback means good', which is closely related to the idea of 'pushing to get the body moving'. However, if we work with the metaphor of 'bowing through a tube', then feedback will be given when the bow approaches the sides of the tube in order to prevent a 'collision'. We will investigate whether users prefer one form of feedback over the other and whether there is a difference in its utility for teaching correct bowing technique.

Another feedback metaphor that we would like to explore is 'hot and cold' and the idea of 'getting warm'. It may be that this metaphor is too closely connected with the idea of finding an object, or a particular point in space, rather than guiding a continuous movement. However, it is also possible that it is easy to interpret and therefore may prove particularly effective as a guide when the pupil explores the bowing movement in real-time.

2) Signalling Low Bow Speed

There is the potential danger that the vibrotactile feedback leads to too low bow velocities, as the student is focused on finding the right trajectory. A possible solution to this problem is to use an additional single vibration motor that signals that the student should increase their bowing speed.

3) Placement of Motors

We will explore how to position the vibration motors most effectively. The right upper arm, close to the elbow, seems a natural location for guiding the bowing trajectory, as the movement of the upper arm plays an important role in the control of this movement. The single motor for stimulating bow velocity will be initially placed on the right wrist or hand. Vibration motors to correct the violin position will be placed on the left hand or arm.

10. CONCLUSION

We have described the current stage of development of a system to support the teaching of good posture and bowing technique to novice violin players. These motor skills are challenging both to teach and to learn. We have demonstrated that using an inertial motion capture system we can track in real-time: i) a player's bowing action (and measure how it deviates from a target trajectory); ii) whether the player is holding their violin correctly. We have described some initial experiments that show that vibrotactile feedback can guide arm movements in one and two dimensions. It seems more effective to use opposing pairs of motors that provide 'pushing' feedback, than to signal separate components of a movement on both motors. We will continue to investigate how best to provide vibrotactile feedback to violin students as it has potential to provide intuitive feedback that does not lead to cognitive overload.

11. ACKNOWLEDGMENTS

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