# Towards a Real-Time System for Teaching Novices Correct Violin Bowing Technique

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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: 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 detail some initial experiments that show that vibrotactile feedback can guide arm movements in one and two dimensions. We then present some preliminary findings from integrating the motion capture and feedback components into a prototype real-time training system. The advantages of vibrotactile feedback are that: i) it does not use the students' visual and auditory systems which are already involved in the activity of music making; ii) it is an intuitive way to guide body movements.**

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

## I. INTRODUCTION

In this paper we describe the ongoing development of a system to support the teaching of correct posture and bowing technique to novice violin players. Our goal is to track the bowing action of the musicians in real-time using an inertial motion capture system and provide vibrotactile and visual feedback to guide their movements along the correct trajectory. Although motion capture technologies have been used in a number of studies of violin playing, our research is novel in several ways. First, in contrast to most music education research into violin bowing, we focus on the movements of the violin players, rather than those of the bow and the violin. Second, our main target group is novice players aged 8-12 years, rather than expert players (that is, musicians at conservatoire level or above). Third, we are investigating how bowing actions can be guided using vibrotactile feedback.

In the next two sections we highlight the challenges involved in learning and teaching correct violin bowing technique. This shows the motivation for designing our system, which aims to address these challenges and support violin teachers and students by providing real-time feedback about the correctness of the bowing action and posture. Section IV focuses on the motion capture component of our system while section V describes how we will use this component with novice violin players. In an initial calibration stage we record the desired bowing trajectories of each student, under the guidance of a violin teacher. We give details of how we use the calibration data to generate a reference, or target, trajectory. In the training stage we use the motion capture system to track the student's bowing movement in real-time and measure how it deviates from the target trajectory. We illustrate how a motion capture system can be used to differentiate between expert and novice bowing. Sections VI and VII describe the development of the feedback component of our system. During training, we 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. Finally, we will describe initial user observations from a real-time prototype system, and indicate challenges and suggestions for improvements for the development of a real-time training system.

## II. CHALLENGES IN LEARNING CORRECT BOWING TECHNIQUE

Novice violin players have to develop a wide range of cognitive and physical skills including: reading music notation; counting notes and rests in order to play in rhythm; learning where to place their fingers on the fingerboard; and listening to whether the note they are playing is in tune. Furthermore, in order to proficiently play a string instrument such as the violin, a musician has to develop precise control of complex arm movements, as well as great postural awareness. Our system aims to help novice violin players develop two motor skills that are foundational for good violin playing: maintaining good posture while playing, in particular holding the violin correctly; and controlling bowing movement.

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 [1]. 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 plays an important factor and should therefore be under the control of the player [2].

Unsurprisingly, learning to play the violin is a long process that requires effective teaching reinforced through extensive practice. 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 [3].

In our research we have initially focused on the particular issue of straight bowing, where the bow remains perpendicular to the strings while being played. This is a task that a novice player needs to be able to accomplish, and forms an important component in learning how to control bowing. Note that we are well aware that expert players will often use subtle and systematic deviations from straight bowing in order to control expressivity and dynamics [2].

## III. CHALLENGES IN TEACHING BOWING TECHNIQUE

Novice violin players traditionally learn how to hold their violin and bow correctly by: i) observing their teacher and trying to imitate their 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. Occasionally a teacher might make pupils feel how to move their arm or hold their instrument by touching them, but this method is discouraged as it might make them uncomfortable. Learning by observation and imitation is challenging for novice players because they often do not know what they are looking for nor 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. A further challenge for the teacher is to communicate clearly to the student how they should move their arm and hold their violin. The verbal feedback often takes the form of a movement metaphor such as: 'windscreen wipers' to describe how a bowing action should not pause at either end of the trajectory; 'paint brush' to emphasize flexible wrist movement; and 'rocket launching' to encourage a more forceful bowing action. The challenge for the student is to translate a linguistic metaphor into a bodily movement.

Our system is designed to address these challenges and support violin teachers and students. We track bowing action and posture with an inertial motion capture system as it is sufficiently accurate for this task and can generate real-time feedback at a far greater rate than a human teacher. We use vibrotactile feedback to guide a student's movement as: i) violinists are already using auditory and visual systems and we want to avoid 'cognitive overload'; ii) it is an intuitive way of guiding body movements that requires little training to understand. We justify these statements in the following sections, initially focusing on the motion capture component of our system.

## IV. 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, based on sensors, motion capture techniques (optical, as well as magnetic field tracking) or combinations of the two [4-7].

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 laptop.

Important requirements for the current application were that the system should operate in real-time, be easy to set up and use, and be portable to allow field studies in environments familiar to the children. For these reasons we chose an IGS-190-M mobile motion capture system from Animazoo [8] (Fig. 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 positions of the joints are computed using a hierarchical model of the human skeleton, which can be fitted to the subject. In the current setup, we used a total of six sensors for effective tracking of the bowing arm, along with the position of the instrument.

## V. MOTION CAPTURE OF NOVICE VIOLIN PLAYERS' BOWING ACTION

A pilot study was performed to compare novice and expert performance of basic bow strokes. The participants were three young violin pupils (each with about two years of practice) and three advanced violinists (all violin teachers). The task was to play sustained notes, with a duration of about 1-3 seconds, on a single string. The participants were dressed in the motion

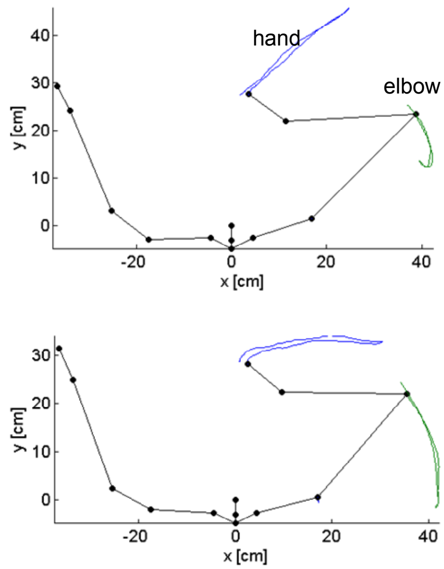


Figure 2. Examples of a good (top) and bad (bottom) basic bow stroke executed by an advanced player, seen from above. The joints and hand of the player, as well as the violin position are indicated by dots, interconnected by lines. The trajectories show the path followed by the hand and the elbow.

capture suit to record their bowing movements, as well as the position of the violin. (Fig. 1).

We found that advanced players were able to bow along a reasonably straight path for most part of the bow stroke, deviating slightly when approaching the tip of the bow, which requires an extended position of the arm (Fig. 2). Furthermore, it was found that the elbow moved along a curved trajectory, reminiscent of a banana shape, which facilitates the production of a straight, uniform bow stroke. In contrast, the novices showed generally a larger range of motion in the upper arm, combined with more stiffness in the elbow, corresponding with the findings of Konczak and colleagues [3]. Furthermore, it was found that the novices used relatively low bow velocities, which can have a detrimental effect on the sound [9].

To generate feedback about a bowing movement, it is necessary to define an appropriate reference or target path. This 'ideal' straight path is individual, depending on a number of factors, such as the build of the player and the way they hold the violin. The definition of the individual reference path is therefore obtained in a calibration recording, in which the teacher guides the bowing movement of the pupil, making sure that the violin is held in the correct position. The reference bowing path is then obtained by fitting a straight line to the measured bowing path. The reference violin position is obtained by taking the average (the violin position should be as constant as possible during the calibration trial).

The fitted reference line subsequently facilitates the extraction of several bowing parameters via geometrical calculations similar to those in [5]. These parameters include the lateral and vertical deviation of the bowing trajectory, the approximate bow velocity (from the projection of the bowing trajectory on the straight line), and an indication of the bow-bridge distance (lateral offset of bowing trajectory). Thus,

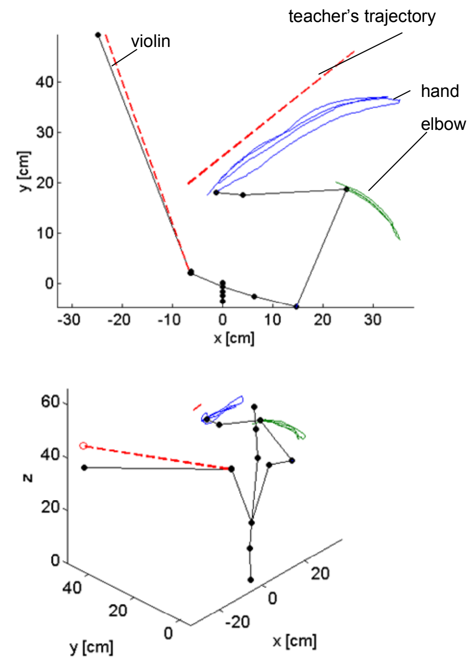


Figure 3. Illustration of bow strokes performed by a novice. (Top) Shows the bowing trajectory as seen from above. The reference bowing path and the reference position of the violin are indicated by dotted lines. (Bottom) The side view clearly shows that the violin position was lowered with respect to the reference position.

feedback can be given on all these aspects, by using appropriate threshold criteria. The reference bowing path should be adapted to the orientation of the violin to make sure that the feedback is adequate. This can be achieved by a transformation of the line parameters based on the measured orientation of the violin.

The principle of the method is illustrated in Fig. 3 which shows 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 that the bow stroke is reasonably straight, but shows a stronger deviation when approaching the tip. Furthermore, the bowing trajectory shows a persistent offset, which might indicate that the pupil was bowing too close to the bridge. The side view reveals that the violin had dropped with respect 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 be to raise the violin and correct the bow movement when approaching the tip.

## VI. Feedback Mechanisms to Guide Movement

As part of the e-sense project (http://www.esenseproject.org) we are building novel augmentation devices to explore sensory, bodily and cognitive extension [10]. We have developed a wearable vibrotactile array and initial experiments have demonstrated that vibrations generated by this device can guide behaviour. There are details of these experiments in [11].

A key finding from these studies is that subjects require very little training (just a few trials) before they are able to effectively use the vibrotactile feedback to guide their arm movements and bat an approaching ball. Another advantage of using vibrotactile feedback in our current system is that this modality minimizes cognitive overload when playing a musical instrument. Other studies on instrument teaching have encountered this problem when using different forms of feedback. For example, the i-Maestro project uses an optical motion capture system, where reflective markers are attached to the bow and the violin to track their movement. An image of a 3D animated violin in motion is shown to the player on a screen, including some additional data on their performance. It was found that musicians had difficulties absorbing the visual information while playing, and preferred auditory feedback. The auditory feedback was given in the form of intermittent alerts because continuous tones strongly interfere with listening to the sound generated by the instrument.

The issue of cognitive overload in music teaching systems is also explored in the work of Sadakata and colleagues [12] who emphasize the value of tools that aid the communication between the teacher and the student during a lesson. They designed visual abstractions relating to expressiveness of rhythmic patterns and used this in a study involving amateur musicians. They found that the limits of working memory mean that a player can only effectively deal with a restricted amount of information in the auditory and visual modalities. It is quite easy to fall into a trap of displaying *too* much information to a student and thereby interfere with the cognitive processes involved in the activity of music making.

We are actively exploring how ‘minimal’ visual feedback can be best incorporated into our system. As part of another project, we carried out user studies to investigate the most effective visualizations for helping novice violin players to play in pitch. We found that incorporating the right amount of ambiguity [13] in the visualizations significantly determines whether they are engaging or frustrating. Too much ambiguity is confusing, as the goal of the exercise is not clear; too little ambiguity can make the experience like traditional rote learning. However, the appropriate amount of ambiguity can be beneficial as it encourages imaginative and active participation in the exercise. These findings are in accordance with other research that has investigated the use of animations to support learning [14].

## VII. Using Vibrotactile Feedback To Guide Arm Movements in One and Two Dimensions

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 involves 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 10mm shaftless DC motor [15], 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. These motors can be updated 10 times per second.

Earlier pilot studies had indicated that two vibration motors, located on opposite sides of the wrist, could effectively guide a hand movement 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 furthest 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).

In the current study we used this ‘opposable motor’ set up to provide ‘pushing’ vibrotactile feedback in the one dimensional task. However, in the two dimensional task one of the motors indicated the left/right (x coordinate) distance from the target and one the up/down (y coordinate) distance from the target. In this set up, in contrast to the one dimensional task, both motors could be active at the same time; the vibration indicates the magnitude of the deviation in a specific dimension, not the direction (hot-cold feedback).

The experimental set up was the same for both studies (Fig. 4). Subjects stand in front of a computer display and see a mirror image of themselves captured by a webcam. In the centre of the display is a circle indicating the starting point of all movements. The subjects wear a coloured glove on their moving hand so that it can 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 subjects move their gloved hand to different locations and the system stores these 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 stored 4 targets in the calibration phase.

During the testing phase, each target is presented once under three different conditions and the system measures the accuracy of the subject’s movement and how long the movement takes. In the first condition (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. In the second condition (visual + vibrotactile), subjects also 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 again move as quickly as possible towards the target and they also receive vibrotactile feedback that indicates how far they are from the target position. In the third (vibrotactile only) condition, 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.

Each subject (n=9) performed the conditions in the same order (visual only, visual + vibrotactile, vibrotactile only) and in every condition each of the 4 targets were presented once in a random order.

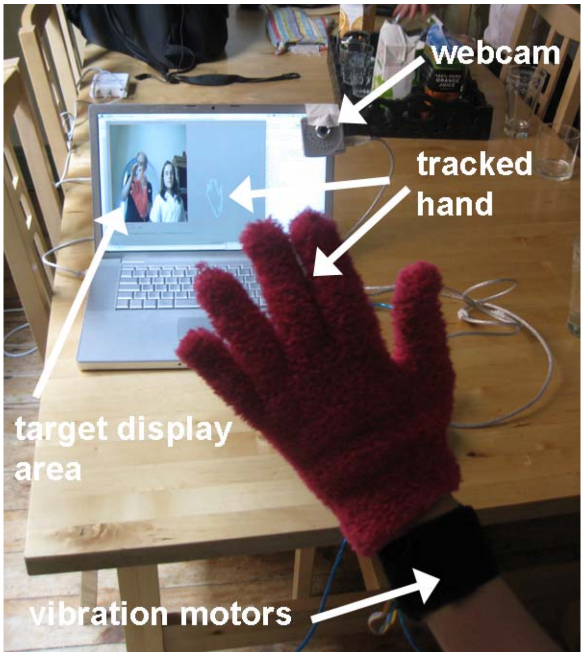


Figure 4. The experimental set up for testing whether two vibration motors could guide arm movements in one and two dimensions. The subject wears a coloured glove on their moving hand that is tracked using a webcam and computer vision software. Subjects position their hand at a central starting point 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.

In the one dimensional task there were no significant differences between the three conditions in the accuracy of the subjects' movements to the targets (repeated measures ANOVA $F(2,16) = 0.38$, $p > 0.05$). A significant effect of time was found ($F(2,16) = 15.88$, $p < 0.0001$). Pairwise comparisons indicated that the vibrotactile only condition took longer to complete than both the visual ($p < 0.05$) and visual + vibrotactile conditions ($p < 0.05$). This is explained by the fact that in the visual only and visual + vibrotactile conditions, subjects perform an initial ballistic movement whereas in the tactile only condition it is a closed loop behaviour where subjects continuously adjust their movement on the basis of the vibrotactile feedback.

In the two dimensional task there was an overall effect of feedback condition ($F(2,16) = 7.06$, $p < 0.01$). Pairwise comparisons indicate that subjects were less accurate in the vibrotactile only condition than in the visual only condition ($p < 0.05$). The decrease in accuracy between the visual + vibrotactile and vibrotactile conditions also approaches significance ($p < 0.1$). These results indicate that it is hard to discriminate two simultaneous vibrotactile signals that are relatively closely positioned on the wrist. There was also a highly significant overall effect of feedback condition on the time taken to complete the task ($F(2,16) = 29.74$, $p < 0.0001$). Pairwise comparisons indicated that the visual only condition was completed faster than both the visual + vibrotactile condition ($p < 0.05$) and the vibrotactile condition ($p < 0.01$) and that the visual + vibrotactile was faster than the vibrotactile alone ($p < 0.01$). The vibrotactile condition was approximately twice as slow as the visual only condition. Again, this can be explained by the fact that in the visual condition the subjects initially perform a ballistic movement. However, it is not clear why the visual + vibrotactile condition was slower than the visual only condition. Possibly, the vibrotactile feedback interfered with subjects' ability to make the initial ballistic movement towards a remembered visual location.

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 took 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.

## VIII. PROTOTYPE TRAINING SYSTEM

In this section we describe the initial findings from integrating the vibrotactile feedback and the motion capture components of our system, in order to guide movement of the bowing arm and the position of the violin. This is a simplified prototype system and acts as a proof of concept. The vibrotactile feedback uses two single vibration motors, rather than opposable pairs of motors as described above. The first vibration motor was placed on the left hand (to provide feedback for the violin position) and the second one was placed on the right (bowing) hand.

An initial test was carried out with two adult professional violinists and a non-violin-player. There was no set task, but candidates were asked to explore playing the violin with vibrotactile feedback. All three candidates reported that they found it confusing to interpret feedback on both hands simultaneously. That is, if the hand holding the violin is in the wrong position, as well as the hand holding the bow, then it is difficult to resolve the situation. An inexperienced player could easily panic under these conditions.

We observed different strategies for using the system. The experienced violinist would feel his way around the beginning of the bow stroke - and only when he had located the reference trajectory (absence of vibration) would he begin the bow stroke and bow as normally, taking notice of the feedback along the way and trying to close in on the target during repeated bow strokes. In contrast, the inexperienced player would continuously search the trajectory during the whole bow stroke; here the closed-loop feedback resulted in a hesitant style of playing, with low bow speed.

Furthermore, it was found that the system was effective in detecting deviations from a straight path when playing at the upper half of the bow (from the middle to the tip), where the distance between the reference path and the actual path becomes large in case of ‘round’ bowing. When playing at the lower half (from the frog to the middle) it was more difficult to detect if the bow was straight or not, as this does not have a great influence on the deviation from the reference path in terms of distance. In the latter case it would be desirable to have a direct measurement of the angle of the bow relative to the instrument in order to provide effective feedback.

The observations led us to the following considerations. Feedback should be prioritized, so that whenever the violin position is incorrect, the feedback only focuses on this aspect, leaving other bowing issues aside. The position of the violin is in this case prioritized because it constrains the correct execution of the bow stroke. Furthermore, feedback on bowing is mainly needed when playing in the upper half of the bow, where the effect of ‘round’ bowing is most prominent.

## IX. FUTURE WORK

We will conduct user studies with novice violin players and their teachers to investigate the usability of the training system and to explore different types of feedback. Furthermore, the current version of the system has a simplified single motor set-up, rather than using opposable pairs. The system is therefore using the metaphor of 'hot-cold', that is, the user knows they are getting warmer or colder, but not in which direction they should move to get nearer the reference trajectory. The next step is to implement the push metaphor with opposable pairs of motors, so that a user receives more precise guidance on how to move.

Another issue to focus on is the strictness of the feedback – feedback that is too strict may create a tense learning situation, and disallow exploration of the student’s personal bowing style. This issue is related to the earlier discussion about helpful levels of ambiguity in the feedback, which can lead to more active participation in the learning exercise.

A key question is whether vibration feedback interferes with the students’ music making activity. In the vibrotactile experiments we have run so far, participants have been able to focus fully on the vibrotactile feedback, and it was at the foreground of the experience. A more realistic scenario is when the feedback occurs while the players is also properly engaged with the music making activity using their auditory and visual sensory systems (see [16] for a discussion of experiments for tactile displays that include distractions).

Finally, we are developing ‘minimal’ visualizations to provide students with feedback on their bowing action and body posture and will be carrying out studies to compare their effectiveness of visual feedback alone at guiding bowing action, as well as in conjunction with vibrotactile feedback.

## X. 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. The results suggested that it is more effective to use using opposing pairs of motors that provide ‘pushing’ feedback, than 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.

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