MusicJacket - Combining Motion Capture and Vibrotactile Feedback to Teach Violin Bowing

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***Abstract*—We describe MusicJacket, a wearable system to support the teaching of good posture and bowing technique to novice violin players. The system uses an inertial motion capture system to track, in real-time: i) whether the player is holding the violin correctly; and ii) the player's bowing action and whether it deviates from a target trajectory. We provide the musicians with vibrotactile feedback about their bowing and posture using vibration motors that are positioned on their arms and torso. We describe a user study with novice violin players which compared a group who were trained using vibrotactile feedback with a control group who only received conventional teaching. We found that vibrotactile feedback is effective at improving novices' straight bowing technique and that half of these subjects continued to show improved bowing technique even when they no longer received vibrotactile feedback. None of the control subjects who received the same number of training sessions using conventional teaching techniques showed a comparable improvement.**

I. Introduction

Motion capture systems can track the movement of the human body and are increasingly being used to help people learn new motor skills, for example, improving performance in a variety of sports, or in rehabilitation applications [1], [2]. Typically, these systems are used to analyze movements, such as a tennis swing, after they have been performed. However, real-time feedback, as opposed to feedback after the event, has been shown to have a more positive effect on the learning of new motor skills [3]. A recent development is the emergence of wearable feedback systems for motor learning, where body movements are tracked and real-time feedback is given in the form of vibration [4], [5], [6]. Two advantages of vibrotactile feedback are that it directly engages the subjects' motor learning systems and that it can reduce cognitive overload [4].

In this paper we describe MusicJacket, a prototype system to support the teaching of good posture and bowing technique to novice violin players. The system tracks a musician's violin position and bowing action in real-time using an inertial motion capture system and provides vibrotactile feedback to guide the player's movements. Violin bowing is a complex movement and it has been reported that novice players need approximately 700 practice hours to master basic bowing skills [7]. The goal of the study described in this paper is to investigate the effectiveness of vibrotactile feedback for teaching correct posture and basic bowing skills to novice violin players, as a first step towards the ultimate aim of reducing the extensive time required to learn the violin. Our expectation was that vibrotactile feedback would provide an intuitive way to guide players' bowing as well as placing them under less cognitive load than the real-time visual or auditory feedback employed in other studies [8]. This is important as a musician's visual and auditory systems are already heavily involved in the process of playing the violin.

The rest of this paper is structured as follows. In the next section we motivate our study and summarize some of the challenges involved in learning and teaching correct violin bowing technique. Section III focuses on related research into wearable feedback systems. In Section IV we describe how our system is set up and we explain how the relevant performance data is extracted from the motion capture measurements. We also describe the rationale behind where we place the vibration motors, and explain the specific performance aspects for which the system provides feedback. In Section V a user study is reported, providing a first evaluation of the effectiveness of the system. Finally, we discuss the challenges we face as we work towards our ultimate aim, which is to use the system in realistic teaching scenarios and assess its effectiveness as a tool for supporting violin teachers in schools teaching 6 to 14 year old children.

II. Background - violin playing

Straight bowing, that is, keeping the bow perpendicular to the string and parallel to the bridge of the violin during playing, is considered as a basic skill, and is typically one of the first things that novice violin players are taught. Mastering a straight bow stroke is a good starting point for the voluntary control of the angle of the bow with the string as observed in the performance of advanced players [9]. Most novice players demonstrate so-called 'round bowing', which makes it difficult to control the contact point between the bow and the string, one of the main control parameters for the quality of the sound. Straight bowing involves a complex movement of the bowing arm, which requires many hours of practice before it is finally mastered. The primary motivation for developing MusicJacket is to develop a technology that makes the teaching and practicing of this basic skill more effective.

In traditional teaching the following three teaching strategies are commonly used for teaching new skills to novice players: i) imitation of the teacher; ii) verbal instructions and feedback; and iii) physical guidance. Sometimes a mirror is used so that pupils can monitor their own performance.

A potential problem with the first two strategies, as well as when using a mirror, is that pupils need to 'translate' their observations and the verbal descriptions of the teacher into physical actions, which is likely to be difficult, given the complex movements required for bowing. The third strategy (physical guidance) provides a more direct way to demonstrate a physical action, but it requires that the pupil relaxes her muscles and passively allows the teacher to guide her movement. The use of real-time vibrotactile feedback offers an alternative strategy. In MusicJacket the actions of the pupil and the feedback they receive are tightly coupled, stimulating them to actively engage in the learning process.

III. Related Work

Vibrotactile feedback has been used to augment virtual and digital musical instruments in order to provide additional feedback to the player and to give the instruments a better, less computer-like 'feel' [10], [11]. Closely related to vibrotactile feedback is haptic guidance, which has been used in a number of music educational approaches. For example, in [12] a percussionist holds a drumstick and this hand is moved by a machine, in order to teach rhythms. Similarly, in [13] the player 'feels' the beat of a polyphonic rhythm in the form of vibrations on whichever limb is supposed to move and hit the drums. Teaching piano skills has been the focus of the Concert Hands system [14], which moves the player's wrists to the required position on the keyboard and uses finger sleeves to signal to each individual finger when to press piano keys. Although these approaches appear to have similarities with MusicJacket, they are quite different as our system provides feedback on the movements made by violin players, rather than providing prompts about when a movement should be made. This gives the player the opportunity to actively adjust their posture or movement in response to the feedback, rather than passively experiencing the feel of the required rhythms or having their hands positioned.

The MusicJacket approach is similar to that employed by other wearable vibrotactile feedback systems used in a wide range of contexts including: motor learning [4]; sensory substitution [15]; collision avoidance in virtual reality games [5]; snowboarding [16]; and rehabilitation exercises for stroke patients [17]. For example, Spelmezan et al. [16] demonstrated that during snowboarding, a person's auditory channel is occupied by listening out for fellow snowboarders approaching from behind or by gauging their performance from the sound of the board on the snow. This suggests that vibration is a good way of providing movement feedback to snowboarders. In their study participants were asked to snowboard down a slope while responding to instructions coming from an instructor standing at the bottom of the slope. The instructor communicated by sending signals through a mobile phone, which were either verbal commands or tactile instructions, for example, the instructor could press the 'lean left' button on her mobile phone and cause a vibration on the right side of the boarder. One of the findings was that snowboarders responded more slowly to auditory commands than to vibrotactile ones.

Whereas in the Spelmezan study a person with a mobile phone decided when to deliver feedback, Lieberman and Breazeal used a motion capture system (Vicon) to track people's motions. The motion capture drives a feedback jacket system for generalized motion learning [4]. They argued that vibrotactile feedback is less abstract than auditory feedback as well as being more immediate, and able to directly engage a subject's motor learning systems. In their study they instructed participants to mimic the position of an expert's right arm, shown in a still image, or to copy an arm movement shown in a short video. They placed a total of eight actuators on each participant's arm, four around the wrist and four around the elbow. The feedback took the form of a 'push', so that if, for example, the wrist was bent too far inwards, then the actuator on the inside of the wrist would start to vibrate until the position was corrected, with a magnitude proportional to the error detected.

Another example of a system with automated feedback is Bloomfield and Badler's tactile sleeve system [5] which helped participants avoid collisions in virtual reality environments. The tactile sleeve was embedded with motion capture markers and 24 actuators: eight on the hand and 16 on the arm, arranged in bands of four. The part of the arm that was in collision with an obstacle was either marked as red, for visual feedback, or was switched into vibration mode.

These nascent systems have been evaluated using quantitative methods. Lieberman and Breazeal's feedback jacket was assessed in terms of the difference between the participants' joint angles and those of the person they were copying. They found that vibrotactile feedback enhanced the performance, independent of the task difficulty. Bloomfield and Badler's tactile sleeve system was assessed in terms of the time taken to complete the task, showing that the group of participants receiving tactile feedback performed better than those receiving no feedback or visual feedback only, and also that they performed better than those receiving both visual and tactile feedback.

Our approach also has similarities with [8], which used motion capture as part of a system to support string teaching. However, in contrast to their approach of tracking the bow and the violin, we track the movement of the player, and rather than providing auditory feedback on aspects of bowing (including straight bowing) we provide the player with vibrotactile feedback. Larkin and colleagues motivate their choice of auditory feedback by comparing it with visual feedback which has the disadvantage that players already have their 'eyes busy' when following musical scores. However, they found that both continuous and short sounds interfere too much with the sound produced by the violin and distracts players, preventing them from using the violin as a natural source of feedback about bowing performance.

The MusicJacket approach is to investigate the effectiveness of vibrotactile feedback in the context of violin playing, which is a highly refined motor skill that takes place in an environment that is rich in sources of natural feedback: the sound of the violin; the vibration of the instrument; and the visual feedback the player receives by looking at their own hands. Rather than trying to control these other sources of feedback, we investigate whether vibrotactile feedback can provide complementary sensory information.

IV. SYSTEM SET-UP AND METHOD

In the light of the motivation for this study and the ultimate objective of using the MusicJacket system as a tool in realistic teaching scenarios, the requirements for the system were that it should be i) able to operate in real time; ii) easy to set up and use; and iii) portable to allow field studies in the class room and at home. These three requirements led us to the choice of the following hardware: an Animazoo IGS-190-M motion capture system[1]; and an Arduino control board[2] to control a set of small vibration motors which can be easily attached to the motion capture suit.

The software integrating the two hardware systems was developed in Open Frameworks, an open source C++ toolkit suitable for the development of real-time applications, in combination with a software development kit (SDK) provided by Animazoo for retrieving and processing the stream of motion capture data. The motion capture data was streamed at a rate of 60 frames per second; the update rate of the prototype software was estimated to be slightly less than 25 Hz on the laptop computer used during the experiments. The latest version of the MusicJacket system includes facilities for synchronously recording the motion capture data and the calculated performance data.

A. Motion capture data representation

The Animazoo motion capture system consists of inertial measurement units (IMUs) containing 3-axis accelerometers and gyroscopes, as well as a magnetometer. The IMUs are attached to a Lycra suit, which allows for flexible placement. The IMUs are connected to a processing unit attached to the suit which computes the 3D orientation data from each sensor and transmits the data to a wireless receiver attached to a PC. Three-dimensional position data are computed from the rotational data of the IMUs using a hierarchical skeleton model, specific to the subject being measured.

In our system setup we only attach sensors to the upper body of the player, and not to the violin or bow itself. Therefore, the violin is represented by the straight line between the left shoulder and hand and the bowing trajectory is represented by the spatial trajectory followed by the right hand (see Fig. 1). The orientation of the violin is considered relative to the upper body of the player (with the Spine1 node as the local origin), so that it is independent of the position and orientation of the player. The bowing trajectory is considered relative to the violin, in order to compensate for movements of the violin, represented as 2D rotations around the left shoulder node (local 'violin' origin).

To generate feedback about a bowing movement, it is necessary to define an appropriate reference or target trajectory. 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 individual reference trajectory is obtained during a calibration procedure in which the player is asked to make a straight bow stroke while holding the violin in the correct playing position. In [18] we describe different ways of achieving a straight bow stroke, but here we use the method where the tip of the bow is placed on the string at a straight angle (see Fig. 2 for violin and bow part terminology). The bow itself remains stationary during this procedure and the pupil moves their right hand along the bow, thus performing the type of arm movement required for proper bowing.

The reference violin orientation is determined from the average line between the left shoulder and the left hand. The reference bowing trajectory is obtained by fitting a straight line to the measured calibration trajectory. The fitted reference line enables the measurement of several bowing parameters, including proximal-distal and vertical deviations of the bowing trajectory from the reference, and approximate bow position (the distance between the frog and the string, approximated by the projection of the performed bowing trajectory on the reference line). The proximal-distal deviation of the bowing trajectory (lower panel Fig. 1) is used as the main measure for the 'straightness' of the bow stroke. A negative deviation indicates that the bow is too close to the body of the player, and a positive deviation indicates that it is too far from the body. The proximal-distal deviation is obtained by projection in the plane orthogonal to the 'violin line' (actual orientation) and the bowing reference trajectory (relative to the actual violin orientation).

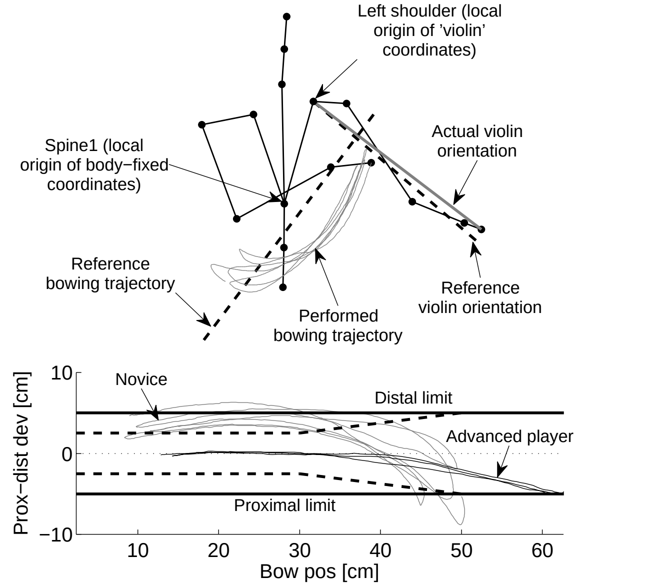

Figure 1. Visualization of the upper body of a novice player, showing the nodes of the skeleton model. The dashed lines (upper panel) show the references of the violin orientation and the bowing trajectory, set during calibration. The gray curve shows an example of a performed bowing trajectory by a novice player. The lower panel shows a two-dimensional projection of the same bowing trajectory which is used to determine the proximal-distal deviation (prox-dist dev.) from the reference (dotted zero line). The tolerance limits are indicated by thick solid lines, forming a tube around the reference. Optionally, the tolerance area can be gradually narrowed to be more strict in the lower half of the bow (dashed line, lower panel). This is achieved by a conical shape of the tolerance limit between 30 and 50 cm in bow position. For comparison, a bowing trajectory produced by an advanced player is shown.

[1] http://www.animazoo.com/
[2] http://www.arduino.cc/

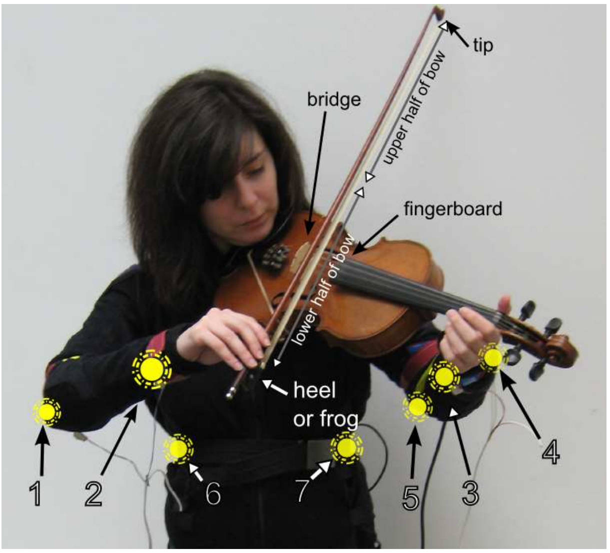

Figure 2. MusicJacket in operation. The positions of the seven vibration motors are indicated (see text and Table I for a detailed description), as well as specific points on the bow and the violin referred to in the text.

Table I
MOTIVATION FOR VIBRATION MOTOR PLACEMENT

Direction	Motor	Motivation
Bowing arm (right), proximal-distal	1 and 2	Motor 1 behind the elbow pushes the arm forward and motor 2 on the wrist pushes the hand back.
Violin hand (left), left-right	3 and 4	Motor 3 on the right side of the wrist pushes it leftwards, and motor 4 placed on the left side pushes the wrist rightwards.
Violin hand, up-down	5, 6 and 7	Motor 5, behind the left elbow, makes the player aware that this arm needs to move upwards. Motors 6 and 7 are placed on the ribs, and stimulate the lifting up of the whole body, including the violin. Note that no feedback is given for the downward movement as this is not a common problem.

B. Vibrotactile feedback

Vibrotactile feedback is provided by a set of seven feedback units, each consisting of a 10 mm shaftless DC motor (310-101 Precision Microdrives) attached to a small circuit board. These units are attached firmly to the participants' arms using Velcro fasteners. The feedback units are connected to an interface board comprising an Arduino microcontroller and two TLC 5940 chips (Texas Instruments) which can drive up to 32 vibration units using pulse width modulation (PWM). The system can set each motor at 4096 different voltage levels, however, while developing the system we observed that most people are only able to reliably discriminate between *off*, *low*, *medium*, *strong* and *very strong*. In the experiments reported here, the motors were either off or set to a strong value so that the feedback clearly indicates when a player has moved away from the desired bowing trajectory or arm position. The interface board is controlled from a laptop computer via a USB connection.

The task of playing the instrument, as well as holding the violin and the bow, impose particular constraints on the movements of the player. This was taken into account when determining where to place the vibration motors on the participants' arms and torso. An overview of the motor positions is shown in Fig. 2, and a description and rationale for their locations is described in Table I.

The main idea behind the feedback is that if the bowing or violin hand is in the correct position, there is no vibration. The motor placement used in this study is a refinement of the opposable pairs approach we described in [19], and is the result of an evaluation with a physiotherapist and a Alexander Technique teacher/professional violinist which focused on finding the locations which resulted in instinctive and appropriate body movements and thereby reduced the time needed to learn how to respond to the vibrotactile feedback. The first four motors are organized as opposable pairs (1-2, and 3-4), indicating the direction of the required correction by pushing the body towards the target position (see Tab. I). The placement of motors 5, 6 and 7 takes into account that often the violin hand has dropped due to the whole body slouching, or the player leaning in on their left foot – hence a stimulation to the ribs provides a general nudge to lift up, and to adopt a straight up position, resulting in the violin hand also rising up. A full discussion of this evaluation is outside the scope of the current paper.

The tolerance margins for the violin position and the bow trajectory can be customized via adjustable parameters. In the experiments described below the tolerance margin for the violin orientation was set at a maximum angular deviation of 7 degrees (corresponding to about 4-5 cm for the left hand), and 5 cm for the proximal-distal deviation of the bowing trajectory. When the violin position or bow trajectory deviate beyond these margins, the player receives appropriate vibrotactile feedback.

V. USER STUDY

We conducted a user study in order to: i) evaluate the effectiveness of our implementation of vibrotactile feedback to guide a user's bowing trajectory and movement of the bowing arm; ii) provide quantitative measures of a player's bowing movements to monitor their level of progress; and iii) assess the robustness of the method. The focus of the analyses is on bowing skills, and not so much on posture and how the players hold the violin. Furthermore, there are a range of usability issues we needed to investigate, in particular whether the jacket is comfortable when playing, and how much time and effort is required to set up the system, including the necessary calibrations.

A. Experimental method

1) Participants: Eight adult volunteers participated in the user study, five male and three female. The participants were all in their mid to late twenties. Two participants had a strong

Table II
OVERVIEW OF TRAINING SESSIONS. THE TEST GROUP RECEIVED VIBROTACTILE FEEDBACK DURING SESSIONS 2 AND 3. THE MOMENTS SELECTED FOR ANALYSIS ARE INDICATED IN THE LAST COLUMN.

Session	Exercises	Vibrotactile Feedback†	Recording
0-a	bow hold		
0-b	bow hold		
1	rhythmic		Before
2	rhythmic	Yes	
3	rhythmic	Yes	Between / During†
4	rhythmic		After

† Test group only.

musical background, but did not have prior experience of violin playing; two participants had occasionally played the violin, but had never received formal lessons; the remaining four participants had no experience of playing any musical instrument. The participants were divided in two groups, a feedback group (coded as T1-4) and a control group (C1-4), which were balanced with respect to the participants' musical experience and gender.

2) Procedure: The experiment consisted of a total of six training sessions for each participant within a period of eight days. Prior to any measurements all the participants were given an introduction to violin playing, spread out over two sessions (sessions 0-a and 0-b), which lasted 40 minutes in total. The initial sessions were primarily concerned with familiarizing the participants with how to hold the violin and the bow. Participants were then taught a series of rhythmic exercises which were played during the subsequent training sessions.

The exercises were designed to use different parts of the bow and were all played on the same open D string. The variations were intended to stimulate the use of different parts of the bow, as well as to divert the participants' attention away from the bowing trajectory. The following five exercises were repeated in all sessions:

- long notes, using the whole length of the bow;
- short notes, using only the lower part of the bow, between the frog (where the bow is held), and the middle;
- short notes, using only the upper part of the bow, between the middle and the tip of the bow;
- a mixed exercise, using a mixture of long and short notes;
- the song 'Hot Cross Buns', consisting of a mix of long and short notes; the rhythm of the song was played on the open D string as the other exercises, ignoring the melody.

Sessions 1 to 4 were all performed in a similar manner. All participants wore the motion capture jacket. In addition, the participants in the test group were equipped with the vibrotactile motors during sessions two and three, as shown in Fig. 2. At the beginning of all sessions the references for the violin orientation and the bowing trajectory were set by performing the calibrations described in Sect. IV-A. The calibrations also served as implicit reminders for the participants of the correct playing posture and how to execute a straight bow stroke. Each exercise was repeated several times with a total duration of about one minute. During the feedback sessions, the exercises were started without feedback, and it was introduced after about 30 seconds. Using this approach it was possible to monitor the performance of the test group with and without feedback guidance.

3) Data analysis: During all sessions the calculated performance data and the motion capture data (BVH format) were synchronously recorded. The calibration data (violin orientation and bowing trajectory) were stored in separate data files. The sessions were also recorded on video for observational purposes.

For the analyses only the long notes and mixed exercises were taken into account, as they require the use of the full range of the bow. The recorded performances were analyzed as follows (see Fig. 3). First, a selection (typically with a duration of 20-30 s) was made, representing the stable parts of the repeated bowing patterns (white area in Fig. 3a). The start of the exercises (typically the first bowing cycle) and transitions where feedback was switched on or off were not included in the selections, as the participants mostly needed some time to establish a stable bowing pattern.

Within the selection, the changes in bowing direction at the tip (bow changes) were automatically detected using a peak picking algorithm (circles in Fig. 3a), and the proximal-distal deviation at those moments (panel b) were collected for subsequent analysis. The main motivation for selecting these points is that the proximal-distal deviation is usually most pronounced at the tip. For example, in Fig. 3b we see that at the tip the deviation ranges from -12 to -15 cm, whereas at other points of the bow it is occasionally within the tolerance margins (-5 to $+5$ cm). The reason for this is that it is typically most difficult when playing in the upper part of the bow to stretch the arm to the extent required for a straight bow stroke (see explanation in Sect. V-C). It can therefore be expected that the feedback will be most helpful in the vicinity of the bow changes at the tip.

The initial performance (*before* measurement) of the participants was determined in session 1. In session 3 an intermediate probe was made (*between* measurement). For the participants in the test group the *between* measurement was determined from the initial part of the exercises when the feedback was disabled; however, they could take their experience of the previous feedback session into account. In addition, the performance of the test group was monitored during session 3 while feedback was enabled (*during* measurement). The final measurement was made during session 4 (without any feedback). A break of at least one day was scheduled between session 3 and 4 in order to determine whether the participants in the test group would retain the benefits of feedback training.

B. Results

1) Guidance effect: Figure 4 shows a clear example of how one of the participants reacted to the vibrotactile feedback. During the first part of the trial, feedback was switched off, allowing the participant to develop his natural bowing pattern. The feedback was switched on after about 38 seconds of playing. The effect can be clearly observed in Fig. 4. Directly after the feedback was switched on the participant interrupted his earlier established behavior, and the feedback seemed to confuse him at first. In particular, in panel (b) we see that before feedback the participant was fluctuating between a -2

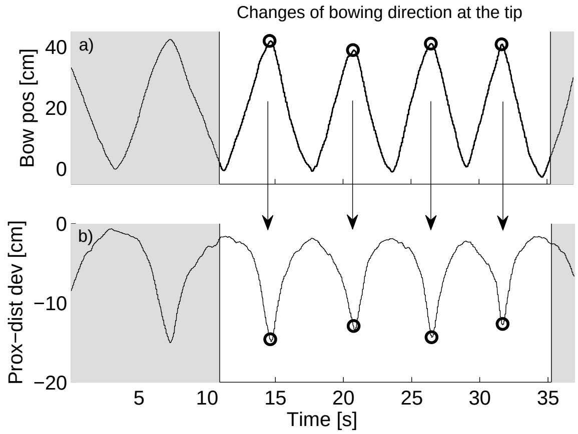

Figure 3. Features extracted for analysis. a) The changes of bowing direction were automatically detected using a peak picking algorithm. b) The corresponding values of proximal-distal deviation were collected for statistical analysis.

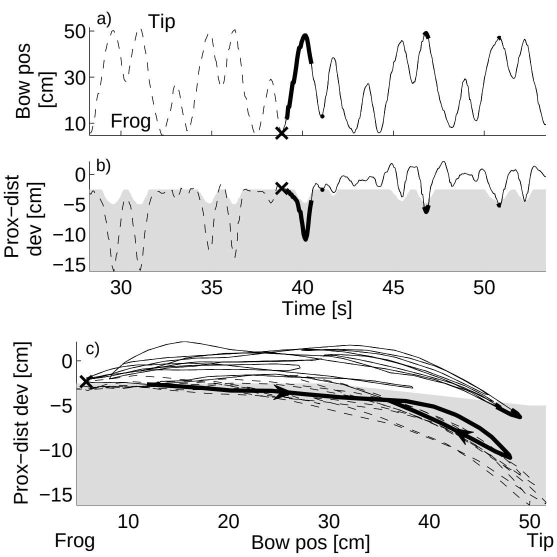

Figure 4. Example of the guidance effect of feedback during about 30 seconds of playing (third session, participant T2). No feedback was applied during the first 38 seconds of the trial, after which feedback was switched on by the experimenter. The panels show: (a) Bow position versus time; (b) proximal-distal deviation versus time; (c) proximal-distal deviation vs. bow position (bowing trajectory). In all three panels the bowing pattern established during the first part of the trial (without feedback) is indicated by a gray dashed line. The feedback part is indicated by a solid line; the crosses indicate the moment that feedback was switched on. The episodes that the participant experienced actual vibrotactile feedback are indicated by thick solid lines. The gray areas in panels b and c indicate the limits of the tolerance region. (In this case a cone-shaped tolerance limit was used, see Fig. 1.)

and -15 cm proximal-distal deviation, but that within 10 seconds he was able to adapt his bowing pattern, and stay between 0 and -5 cm, which is within the tolerance limits. In panel (c) the effect is shown to be most notable in the upper half of the bow (bow position range 30-50 cm). The change in pattern was achieved by the participant stretching his arm more when approaching the tip.

2) Comparison between test and control group: Fig. 5 shows an overview of the achievements of the participants

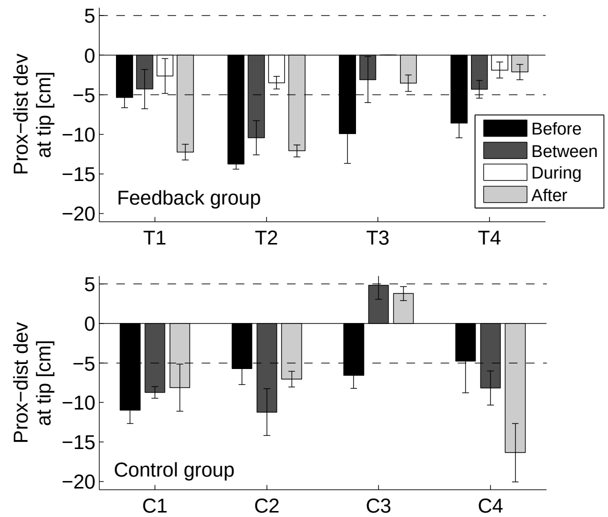

Figure 5. Results at different moments during the experiment for the test group (upper panel) and the control group (lower panel), consisting of four participants each. The data represent the proximal-distal deviation at the tip from the set reference; the tolerance limits for feedback are indicated by the dashed lines. The error bars represent the 95% confidence intervals of the means; the number of collected data points ranged from 7 to 36 per condition. (For participant T3 no measurements were available during feedback, as the prototype used at the time did not facilitate data recording.)

in the feedback and the control group during the course of the experiment. Fig. 5 shows for each participant the proximal-distal deviations relative to the set references averaged across selected portions of the long notes and mixed exercises. The threshold for feedback, which was set to 5 cm in the vicinity of the tip, is indicated by dashed lines.

The following observations can be made from Fig. 5. At the beginning of the experiment (*before* measurements) all participants showed a proximal-distal deviation close to or outside the set tolerance region of 5 cm at the tip. For the feedback group there was a clear difference between the *before feedback* and *during feedback* conditions [$p < 0.01$, two-sample t-test]; the proximal-distal deviation was in all cases reduced and remained well within the 5 cm tolerance region during feedback (white bars in upper panel). This is an indication of that the participants in the feedback group could effectively take the feedback into account.

We found no significant differences between the feedback group and the control group comparing the before and after measurements, and the data showed no consistent learning effect for both groups. However, some trends could be observed. The feedback group showed a gradual progress during the subsequent sessions, indicated by a decrease of the proximal-distal deviation. All participants in the feedback group showed a smaller deviation during the *between* measurements compared to the before measurements, and the lowest deviations were obtained during feedback. In contrast, the general trend for the participants in the control group was less clear, and only participant C1 seemed to make a slight progress in the course of the experiment.

In the *after* measurements two of the participants from

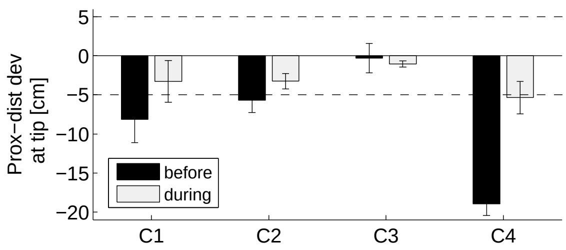

Figure 6. Results for feedback received by the control group after 4 completed sessions without feedback, showing a clear effect of the feedback (during vs. before).

the test group, T3 and T4, seemed to have made persistent progress compared to the *before* measurement after an interval of at least one day after they received vibrotactile feedback. For participant T2 there was no clear difference between the *after* and *before* measurements, confirming the impression of the experimentators that he was falling back into his old habits. Participant T1 showed the largest proximal-distal deviation during the last session, which might, however, be partly explained by a slightly skewed bowing reference line (for a discussion see Sect. V-E).

The participants in the control group did not show any obvious overall progress for the duration of the experiment.

3) Extra feedback session control group: After the formal part of the experiment was finished, we were interested to see how the participants in the control group would react to the feedback, after having had more time to establish their own 'natural' behavior. The results are shown in Fig. 6. The same procedure was used as for the participants in the test group; during the initial part of each trial there was no feedback, and feedback was switched on after the participants had developed a stable bowing pattern. Interestingly, the participants were able to adapt to the feedback quite quickly, and the proximal-distal deviations dropped immediately by a significant amount under influence of feedback. In all cases the average proximal-distal deviations were close or within the set tolerance limit of 5 cm while the participants received feedback, in accordance with earlier observations of the feedback group.

C. Relation with bowing arm coordination

1) Arm angles: Figure 7 shows a simplified 2D model of the arm movement required for a straight bow stroke. It can be seen that in the lower half of the bow (points 1-3), the movement is mainly achieved by angling the upper arm outwards, whereas in the upper half of the bow (points 3-5) the movement is dominated by the forearm. For a perfectly straight bow stroke, the upper arm has to angle inwards again, in order to achieve the required extension. This typical movement results in a specific relation between the upper arm angle and the elbow angle, which is shown in the lower panel. The exact shape of this relation is dependent on the length of the different parts of the arm, the angle at which the violin is held and the contact point between the bow and the violin.

It should be noted that the final extension required for a straight bow stroke all the way towards the tip is quite unnat-

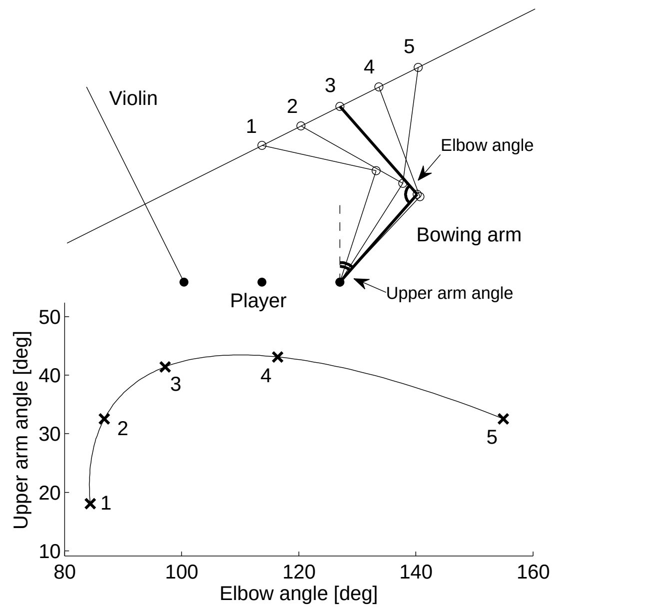

Figure 7. Basic movement pattern (2-dimensional model, top view) of bowing arm required for a straight bow stroke (upper panel) and corresponding behavior of the arm angles (lower panel). In the lower half of the bow (points 1-3) the movement is dominated by the upper arm and in the upper half (points 3-5) by the lower arm (elbow angle). For comparison, the player in Fig. 2 would be in the vicinity of point 2.

ural, and it can be commonly observed in the performance of professional players that they do not normally move the upper arm forward as shown between point 4 and 5, resulting in a slightly curved bow stroke close to the tip (see for example the bowing trajectory produced by an advanced player in Fig. 1).

In Fig. 8 the relation between the arm angles is shown for two examples of 'good' bowing and 'crooked' bowing, produced by an experienced player. In the case of crooked bowing, characterized by an extreme roundness of the bowing trajectory, the upper arm dominates the movement throughout the entire bow stroke, whereas in the good bowing example the elbow is more active, and the curve in Fig. 8 shows a high degree of resemblance with that predicted by the model shown in Fig. 7 (lower panel).[3]

2) Example from user study: An example of the coordination of the arm angles of one of the participants in the user study is shown in Fig. 9. The curves show a remarkable evolution during the course of the experiment. In session 1 (*before* measurement) the movement was dominated by the upper arm, which indeed resulted in rather round bowing trajectories. There was a striking difference between the *before* and the *between* measurement; in the latter the relation between the arm angles shows typical features of a straight bow stroke. This provides a strong indication that the player had adapted her arm movements in order to achieve a straight bow stroke

[3]For comparison with the results presented by Konczak et al. [7], it should be noted that the measurements presented by the latter only represented a small part of the curve, i.e., the players in that experiment seemed to have used only a small part in the middle of the bow. However, the coordination of the arm angles in a bow stroke using the full length of the bow is rather complex, and cannot be described by a mere 'freezing' of the movement of the upper arm, as suggested in [7].

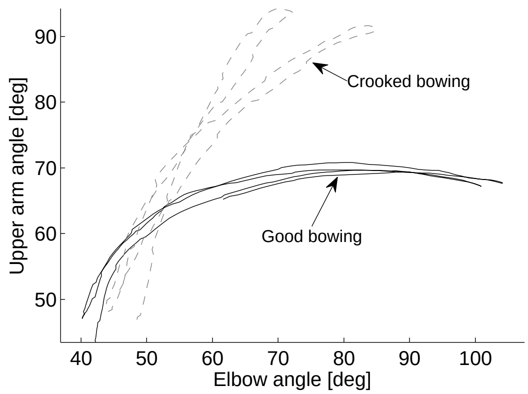

Figure 8. Typical examples of arm angles for crooked bowing (upper panel) and good bowing (lower panel), produced by an experienced player.

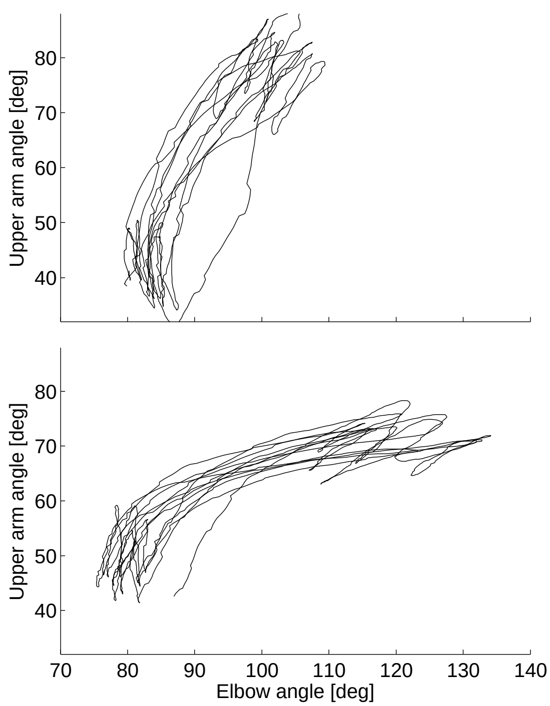

Figure 9. Arm angles produced by participant T3 in the mixed exercise during the *before* measurement (upper panel) and the *between* measurement (lower panel).

under influence of the feedback. In the *after* recording (not shown), this behavior was still present, indicating that the participant could reproduce the newly learned coordination of the arm movement without feedback.

D. Qualitative observations

Some of the participants who received feedback began to talk about the movement of their bowing arm; particularly about changing the angle of the hand, fingers or wrist and a need to extend the elbow. This aspect of body awareness was not expressed in the same way by any participants in the control group. Most participants also noted that they experienced most feedback at the extremities of the bow – either the heel or the tip. This meant they knew where they had to focus their attention when practicing. An unforeseen and undesirable consequence of this was that some participants chose to reduce the amount of bow they played to avoid feedback, rather than changing the angle of their bow at the tip or heel. One of the control participants also mentioned it was harder to play near the tip so this is something which is noticeable even without vibrotactile feedback but perhaps less obvious. In general participants seemed to think the feedback was helpful and one in particular said "if I was to keep playing I would choose with feedback … because it's useful".

E. Robustness of the method

Regarding the robustness, we need to establish whether the calibration method for setting the reference is accurate enough, and whether the set references are valid for the duration of a typical session (about 30 minutes). The robustness of the method is mainly dependent on: i) the accuracy of the motion capture measurements; and ii) the quality of the references set during calibration. Concerning the first, the accuracy of position measurement is critically dependent on the correctness of the skeleton model used. In the study individual skeleton models were constructed for each participant, using a standard procedure and software provided by Animazoo. Another issue with inertial motion capture systems is drift, which is often compensated for by Kalman filtering in some form. In the Animazoo system the processing takes place in the processing unit attached to the body of the player and unfortunately details about the signal processing are not disclosed by the manufacturer.

In the majority of cases the motion capture system seemed to produce valid data. However, in some cases drift problems occurred, visible as strange deformations of the skeleton, especially in the lower back. Despite that, the quality of the feedback produced by MusicJacket seemed to be quite resistent in most cases, which can be explained by the fact that the spine1 node (in the middle of the back, see Fig. 1) was used as a local origin in the current implementation. In case of obvious drift problems, the data were discarded from further analysis. In order to avoid drift problems the procedures specified by the manufacturer were strictly followed, and it was made sure that the sensors were tightly attached to the body of the player.

Concerning point ii), a manual calibration procedure is performed in the beginning of every measurement session (see Sect. IV-A). The procedure requires that the person who performs the calibration has 'a good eye' for straight angles, and is able to correctly monitor the posture of the player and guide her movements during the calibration. An incorrectly performed calibration procedure might lead to offset and/or skewed references, which will affect the accuracy of the extracted features, as well as the correctness of the feedback.

As explained in Sect. IV-A the orientation of the violin is represented by the line between the left shoulder and the left hand. The bowing trajectory reference is adapted to the current orientation of the violin to ensure correct feedback even in case of naturally occurring fluctuations in the violin orientation during playing. This way of representing the orientation of the violin requires that the instrument is stably resting on the shoulder; the correctness of the references will degenerate when the violin slides down from the shoulder. This requires some basic skill from the player. In the present user study this formed an important part of the initial training (session 0-a and 0-b) preceding the experiment.

During the user study, it was made sure that valid references were used by judgment of the appropriateness of the feedback, which was continuously monitored by the experimenter(s). For future work alternative calibration procedures will be tried to guarantee the robustness of the method.

VI. Discussion

The user study provided some strong indications of the potential of our approach. It was shown that all participants receiving vibrotactile feedback were able to quickly take it into account. Furthermore, it was shown that the coordination of the bowing arm was improved by the feedback, and the verbal reactions from the participants indicated that the feedback enhanced their body awareness. This provides support for the notion that vibrotactile feedback supports the process of motor learning.

The learning effect persisted in the post-feedback measurements in two of the participants from the feedback group. The other two participants did not show a persistent effect during the final session when playing without feedback. This is not surprising when the short period of time over which the experiment took place is compared to the extensive amount of practice it normally takes to develop basic playing skills. It remains to be investigated how much exposure to vibrotactile feedback is required before the skill is fully internalized. The required amount of practicing (either with or without feedback) is of course also likely to be dependent on the individual.

A potential danger of feedback systems such as MusicJacket is that players could become dependent on them. It is however more plausible that the feedback will help novices to internalize the correct movement, as they are stimulated to actively produce it. Repeated performance will stimulate their proprioceptive memory of the correct movement, which then becomes reproducible without feedback. We intend to explore whether a more gradual removal of the feedback, or an approach where the player takes more responsibility for switching the feedback on or off themselves leads to a more lasting effect.

Another finding of the user study was that the participants had difficulties dealing with simultaneous feedback about the violin orientation and the bowing trajectory. This problem could be resolved by delivering the feedback in stages – first on the violin orientation to ensure that the violin is in the correct position, and then on the bowing trajectory. However, we have not fully explored how best to handle the relationship between these two aspects of bowing technique. Our hypothesis is that 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 prioritized because it constrains the correct execution of the bow stroke.

VII. Conclusion and Future Work

We have described a prototype system that combines motion capture and vibrotactile feedback technologies to support the teaching of good posture and bowing technique to novice violin players. The presented user study shows that vibrotactile feedback was quickly understood by the participants and provided good guidance of basic (straight) bowing motion. It can therefore be concluded that our system has potential for teaching basic violin playing skills.

Furthermore, the user study resolved usability issues we set out to explore: the participants found the system comfortable to wear; putting on the MusicJacket did not take much time; and the calibration method was a relatively straightforward procedure to carry out.

Although this paper shows the feasibility of the MusicJacket system, further research is required to get a proper evaluation of the effectiveness of the approach and its usability in a real teaching setting. To provide further insight into the educational potential of the system, as well as to gain valuable feedback from violin teachers, we are currently running a user study with participants from our target group – novice violin players aged between 6 and 14 years old.

We are also actively exploring how our approach of real-time feedback can be generalized and applied to other application domains in which posture and motor learning skills are important. In particular we are exploring the teaching of other musical instruments such as the cello or the flute, as well as singing, ballroom dancing and a movement therapy for patients suffering from depression.

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