

# Why do we need 5-DOF force feedback? The case of violin bowing.

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## Abstract

*The analysis of gestures associated with playing musical instruments can provide insight into the haptic cues used to exercise control over acoustic parameters. In this study, forces acting on the bow as experienced by the violinist are described based on an analysis of bowing gesture motion capture data in crescendo-decrescendo notes, finally leading to a formulation of criteria for haptic virtual bow controllers.*

## 1 Introduction

In playing a musical instrument, the player exerts control over a set of sound-related parameters which determine the nature of mechanical vibrations induced in some physical body. It has been shown that the bowing gesture in particular allows very accurate control over many timbral aspects of the resulting sound wave [4, 7]. Cadoz [2] observed that a sound is defined by the producing musical gesture, and that this gesture is accompanied by inherent haptic feedback, which is what allows the player to exert such fine control. However, in a bowed instrument, the control parameters (human-bow interaction) are once removed from the sound parameters (bow-string interaction), and so it is interesting to look at how forces are transferred indirectly from the sound producing mechanism through the bow to the player and vice-versa. An examination of the movements of the bow during violin playing have allowed us to identify correlations between sound and control parameters, while further analysis has revealed several directions of haptic forces at work throughout the gesture.

O'Modhrain [6] has used a 2-degree-of-freedom (DOF) haptic device to experiment with the effects of friction on bowing, and found that, although a Helmholtz friction model had little effect on bowing performance, players preferred the presence of friction over the non-friction case. This could be interpreted to imply that the force feedback of the virtual wall used for bowing may have provided adequate information to the player for execution of the bowing gesture, while the precise nature of bowing friction, much of which is filtered out through the bow, plays a less important role

than the net resistance experienced by the player's right hand.

We will discuss some additional haptic cues, derived from the previously-mentioned control parameters, which provide DC-frequency force feedback to the player. These cues exist both in linear directions as well as in torsional forces, felt by the player's bowing hand. Some of these cues, such as detents, have previously been explored [5]; however, we will discuss several additional force vectors observed, illustrated by an analysis of bowing gestures during crescendo-decrescendo bow strokes. Finally, we will discuss the implication on hardware requirements for accurate haptic rendering of the bowing gesture.

## 2 Bow coordination in violin playing

### 2.1 Measurement of bowing gestures

The position and the orientation of the bow and the violin were measured using a Vicon 460 optical motion capture system. Six cameras (type M2) were used, four in front of the player and two behind. During the measurements five markers were placed on both the violin and the bow. In order to measure the full orientation of the bow, two of the markers were placed on small antennas mounted on the stick, to avoid collinear placement of the markers. During the calibration extra markers were placed to indicate the positions of the bow-hair onset at the frog and the tip (bow) and the positions where the string crosses the bridge and the nut (violin). During the post-processing these positions could be reconstructed as virtual markers for all recorded trials.

The local reference frames of the violin and the bow are shown in Fig. 1. The respective origins correspond to the virtual markers on the bridge (violin) and the frog (bow). The axes were chosen to represent physically meaningful directions, e.g. along the string (y-axis of the violin) and the bow hair (x-axis of the bow).

Bow velocity was calculated from the relative velocity of the bow and the violin, projected on the local x-axis of the bow. The bow-bridge distance was calculated as the distance between the bow-string contact point and the local origin of the violin.

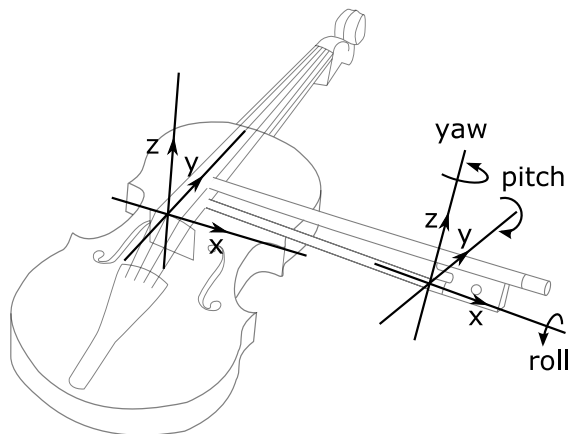


Figure 1: Local reference frames of the violin and the bow. The bow angles skewness (yaw), pitch and tilt ( $-$ roll) correspond to the orientation of the bow relative to the violin.

The bow angles (skewness, pitch and tilt) were calculated from the orientation of the bow relative to the violin. In the chosen geometrical representation of the violin and the bow, these angles have a direct relationship with the Tait-Bryan (or Euler) angles, obtained by respective rotations around the z-axis (yaw), y-axis (pitch) and x-axis (roll) in the local frame of reference (in this case the bow, with the orientation of the violin as starting point). The bow angles are then defined as follows: skewness (angular deviation of the bowing direction) equals yaw, pitch (angle associated with string crossings) equals pitch, and tilt (tipping of the bow, so that the bow hair is no longer flat on the string) is defined as negative roll. According to the latter definition tilt is positive when the stick is rotated away from the player, which is normal in violin playing.

Bow force was measured using a custom made sensor mounted at the frog of the bow. The sensor consisted of a spring leaf equipped with strain gages on both sides. The sensor was mounted so that the spring leaf was pressed against the bow hair, measuring the flex of the bow hair. The sensors' output signal was calibrated by pressing the bow on a calibrated force transducer at different bow positions. A calibration function was fitted to these measurements, yielding the coefficients needed to calculate the bow force as a function of bow position.

Mocap data was recorded at a frame rate of 250 Hz. The force sensor signal was measured at a sample rate of 10 kHz on a different computer. The measurements were synchronized by generating a pulse at the start of each trial using a pushbutton. The pulse was recorded in separate channels on both devices, enabling a posteriori alignment of the data.

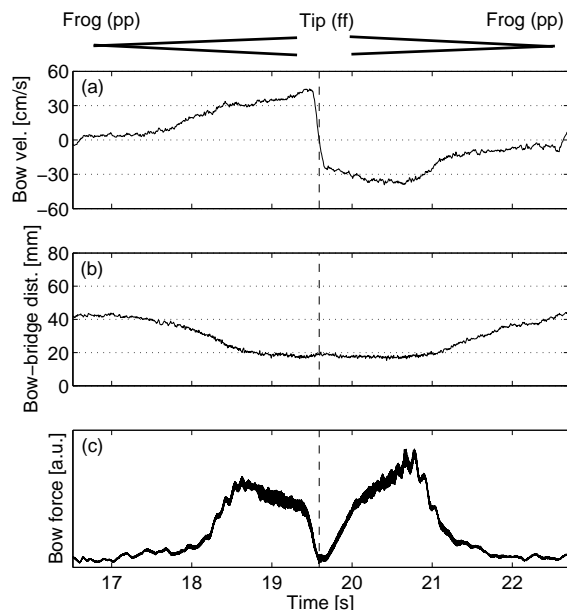


Figure 2: Coordinated change of the main bowing parameters during crescendo-decrescendo tones (down-up): (a) bow velocity, (b) bow-bridge distance, and (c) bow force. Bow position and dynamic level is indicated above the panels. The change in bowing direction (from down to up) is indicated by the dashed vertical line.

## 2.2 Crescendo and decrescendo notes

Crescendo and decrescendo notes form a good example of the coordination of bowing parameters [1]. An increase of the perceived loudness of a tone mainly involves two factors: (1) an increase of the amplitude of string vibration, and (2) reinforcement of the higher harmonics of the tone (timbre). In terms of bowing parameters the first is achieved by increasing bow velocity and/or decreasing bow-bridge distance (the amplitude of the string vibration is proportional to  $v_B/\beta$ ), while the second is mainly achieved by increasing bow force.

In practice, a change of dynamic is mostly a combined effect of changes of these bowing parameters. This is clearly illustrated in the following example. A violinist (advanced music student) was asked to play a series of long crescendo-decrescendo notes, first down-up (crescendo during down bow) and then up-down (crescendo during up bow). All notes were played using the entire length of the bow. In Fig. 2 the bow velocity (a), bow-bridge distance (b) and bow force (c) are shown for one down and up bow somewhere in the middle of the series of notes. It can be seen that the bow velocity was low in the beginning of the down bow (pp) and increased until the change of bowing direction (ff). The up bow started with a high bow velocity (ff) and decreased towards the end of the note (pp). Simultaneous with the increase of velocity during the down bow, the bow was

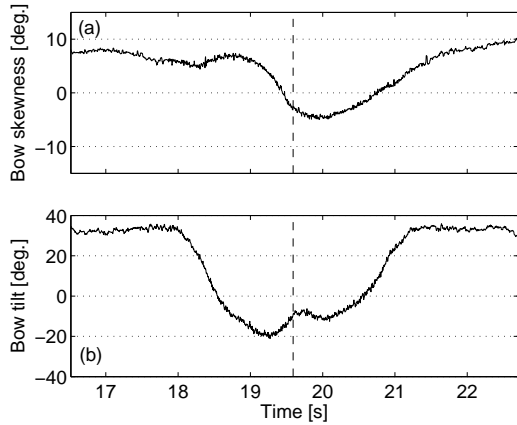


Figure 3: Bow angles during crescendo-decrescendo (down-up): (a) skewness, and (b) bow tilt. The change in bowing direction is indicated by the dashed vertical line.

moved closer to the bridge and the bow force was increased. During the up bow (decrescendo) the bowing parameters changed in the opposite direction.

Figure 3 shows bow skewness and tilt during the same bow stroke. Arguably, tilt has less influence on the sound than the above-mentioned main bowing parameters (see e.g. Schoonderwaldt et al. [8]) and skewness has acoustically at most a deteriorating effect on the sound. However, as *control* parameters they can play a considerable role in violin playing. In Fig. 3 (a) it can be seen that the skewness was mostly positive during both the down and the up bow, i.e., the bow was angled away from the player. This causes a drift of the contact point, due to the stick-slip interaction between the bow and the string, facilitating the (continuous) change of the bow-bridge distance.

Also, the bow tilt (Fig. 3 (b)) was changed during the bow stroke, apparently in coordination with bow force. The relation can be explained as follows: in order to play softly close to the frog, tilting the bow facilitates the control of bow force as a smaller portion of the bow hair is in contact with the string. As a result the bow becomes more compliant reducing the effect of small bowing inconsistencies. However, at the tip, a high bow force is more easily obtained with the hair flat on the string.

Figure 4 shows the crescendo-decrescendo in opposite bowing direction (up-down). Comparison with Fig. 2 reveals that a similar strategy was used to achieve the changes in dynamic: the bowing parameters show the same trend except that the bow velocity is opposite in sign. In contrast, the control parameters shown in Fig. 5 were markedly different than the control parameters in the opposite bowing direction (Fig. 3). The skewness (Fig. 5 (a)) was negative (angled towards the player) for the same reason as before: the direction of the drift of the contact point changes with bowing direction. This

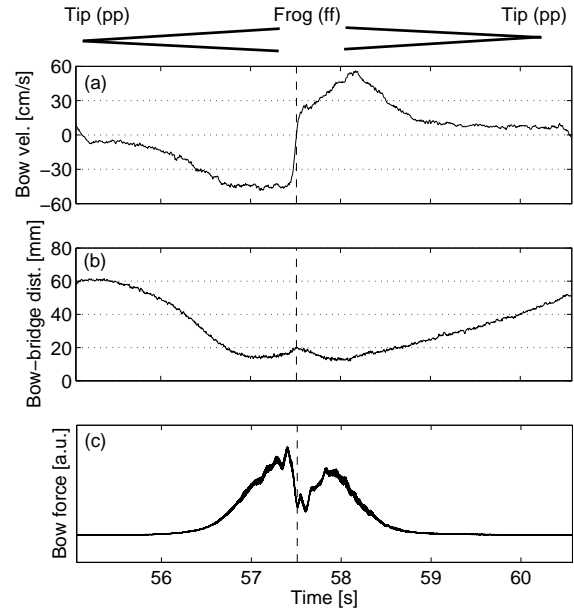


Figure 4: Coordinated change of main bowing parameters during crescendo-decrescendo tones (up-down): (a) bow velocity, (b) bow-bridge distance, and (c) bow force.

is a strong indication that skewness—in these particular cases—was used as a control parameter to facilitate a continuous change of bow-bridge distance.

A different behaviour of bow tilt (Fig. 5 (b)) was also observed: in the second example, the tilt angle was overall much smaller. Only close to the frog the bow was slightly tilted, in this case probably to facilitate the bow change. The relation with bow force is less important here, as it is much easier to exert a high bow force close to the frog.

### 3 Forces acting on the bow as felt by the player

The forces exerted on the player's bowing hand during crescendo can be decomposed into Cartesian force vectors as seen in Figure 1. As described in section 2.1, the bow may be oriented in space according to three axes: pitch, yaw, and roll. Each of these orientations may be associated with a torque felt by, and exerted by, the player.

During a bow stroke, there is a non-zero net displacement of the string in the direction of bowing (x-axis), due to static and dynamic friction. This friction is modulated by the bow pressure, which is a downward force (z-axis). This is complemented by the string's upward normal and spring constant which counters the force of gravity and reacts to the bow pressure.

However, since the bow's frog lies some distance from the bow-string contact point, the downward bow

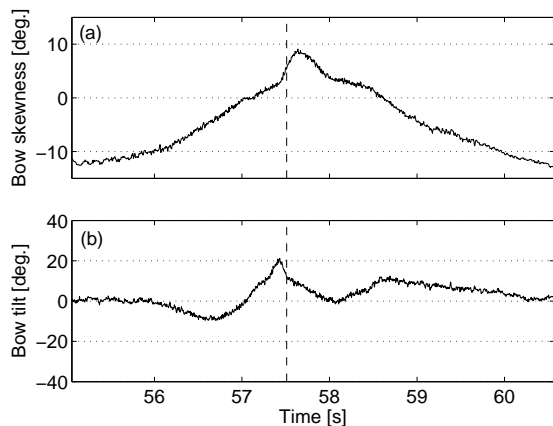


Figure 5: Bow angles during crescendo-decrescendo (up-down): (a) skewness, and (b) bow tilt

pressure is exerted by a torque in the pitch direction, mediated by the index and pinky fingers. This torque is associated with the compliance of the bow and the string experienced by the player when pressing the bow into the string. This lever mechanism means that the player can exert less force toward the tip of the bow. Consequently, considering the examples in section 2.2, a crescendo will come more naturally for the player during an up bow. Additionally, as described and implemented by Nichols [5], the pitch axis in combination with the vertical direction also allows the player to feel the location of the strings (detents).

We saw that the presence of skewness in the bow's yaw orientation creates pull on the bow along the string, felt as a torque by the player, causing the hair-string interaction point to drift. After change of bowing direction, this drift will also occur in the opposite direction. However, it is often the case that after some amount of horizontal movement, the player will preemptively counter this drift by applying an opposing torque. Furthermore, when bowing straight the contact with the string keeps the bow from moving in lateral direction.

In cases where the player has employed bow tilt, downward force is accompanied by a slight torque in the roll direction, created due to the stick-hair orientation no longer being in parallel with gravity. Changes in tilt also affect the number of hairs in contact with the string, which in turn changes the vertical spring constant as well as the frictional resistance to orthogonal movement across the strings.

## 4 Conclusions

We have reviewed some aspects of control gestures in violin bowing and described observations of their use in co-occurrence with changes to sound-related bowing parameters. We have also described some aspects of force feedback experienced by the player in relation to these control gestures.

Previously, apparatus supporting force in two [6], three [3], and four [5] degrees of freedom have been used for implementing virtual bowing interactions. We suggest that this is not sufficient for a complete simulation of forces experienced by the player; the above analysis shows that torque is felt in all three rotational directions: pitch, to feel string detents and to apply vertical pressure; yaw, in relation to changes of bow-bridge distance; and roll, when tilt is employed. Combined with two of the three linear directions (frictional force and compensation for gravity), it becomes clear that it is necessary to employ force in at least five axes when synthesizing a virtual haptic representation of the bowing gesture, with freedom of movement in the lateral direction. Future experiments with 6-DOF force feedback devices are planned to assess the relative importance of the forces and torques experienced by players.

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