String Bowing Gestures at Varying Bow Stroke Frequencies: A Case Study

Nicolas Rasamimanana[1], Delphine Bernardin[2], Marcelo Wanderley[2], and Frédéric Bevilacqua[1]

[1] IRCAM, CNRS - UMR 9912, 1 Place Igor Stravinsky, 75004 PARIS, France
{Nicolas.Rasamimanana, Frederic.Bevilacqua}@ircam.fr
[2] IDMIL/CIRMMT, McGill University, Montreal, QC, Canada
{Delphine.Bernardin, Marcelo.Wanderley}@mcgill.ca

Abstract. The understanding of different bowing strategies can provide key concepts for the modelling of music performance. We report here an exploratory study of bowing gestures for a viola player and a violin player in the case of bow strokes performed at different frequencies. Bow and arm movements as well as bow pressure on strings were measured respectively with a 3D optical motion capture system and a custom pressure sensor. While increasing bow stroke frequency, defined as the inverse time between two strokes, players did use different bowing movements as indicated from the measurement of bow velocity and arm joint angles. First, bow velocity profiles abruptly shift from a rectangle shape to a sinus shape. Second, while bow velocity is sinusoidal, an additional change is observed: the wrist and elbow relative phase shifts from out-of-phase to in-phase at the highest frequencies, indicating a possible change in the players coordinative pattern. We finally discuss the fact that only small differences are found in the sound while significant changes occur in the velocity / acceleration profiles.

1 Introduction

The understanding of different bowing strategies can provide key concepts for the modelling of music performance. Such model can be applied in music pedagogy [1] or in the design of novel musical interfaces [2]. We previously reported the study of three standard bowing techniques in violin playing [3]. In particular, we discussed issues on gesture "continuity". This concept relates to the fact that an expert violinist is able to play several and subtle variations between two bowing techniques, e.g. *Détaché* and *Martelé*. We showed in reference [3] that such subtle variations can be directly tracked in the bowing dynamics and described with features derived from bow acceleration profiles.

In this paper, we report complementary results on violin playing by studying bowing gestures, i.e. movements directly involved in sound production, at different stroke frequencies and further question the concept of gesture "continuity". Slow bowing generally requires a relaxed right arm. Nevertheless, it is usually recognized among bowed string players that rapid, repeated bow strokes can require the right arm to be tensed up. Such strategy is usually used to achieve a given rhythm, for example four sixteenths, or to perform a *tremolo*. From the players' viewpoint, these are different arm movements to perform cyclic, repetitive bowings. We here test this hypothesis with the study of an *accelerando/decelerando*, i.e. bow strokes performed with an increasing/decreasing frequency, and investigate on the continuity between slow and fast bowing.

The paper is structured as follows. First we describe related works and our experimental method based on optical 3D motion capture technology combined with a bow pressure sensor. Second, we present and discuss results obtained by measuring arm and bow movements of two instrumentalists. Third, we investigate sound characteristics at different bow stroke frequencies. Finally, we present conclusions and directions for future work.

2 Related works

When performing a *glissando*, it may happen that singers produce a discontinuity in pitch. It corresponds to the transition from one laryngeal mechanism to another, such as described in reference [4]. This drastic change in voice production enables singers to achieve the highest frequencies of the *glissando*. We hypothesize that a similar phenomenon occurs for bowed string instruments: players can change their bowing gestures to perform high bow stroke frequencies.

This configuration change in voice production relates to a well-known notion in motor control: the reorganisation of coordinative patterns, as occuring in gait shifting. In particular, Kelso studied the abrupt phase transitions in human hand movements according to the cycling frequency [5, 6]: for example, a periodic out-of-phase movement of human's fingers, i.e. one finger up while the other is down, shifts to an in-phase movement, i.e. both fingers up or down at the same time, when increasing frequency. These results are especially insightful for our study as we are dealing with a cyclic movement with increasing frequency (*accelerando*), and involving the upper arm, the forearm and the hand.

Several studies report on the movement analysis of instrument performance [7, 8], [9], [10] and in particular bowed string players [11]. Winold et al. [12] first studied coordination issues in bow arm movements in a musical context. They analyzed cellists' bowing coordinations while performing fragments by Brahms and Schubert at different tempi. They concluded that increasing tempi produced a proportional scaling of stroke amplitudes and durations. Nevertheless, they did not notice any change in within-limb coordinations. More recently, Baader et al. [13] studied coordination between fingering and bowing and showed anticipatory movements between the left hand and the right arm. While our approach is similar to Winold's, we here focus on bow, elbow and wrist movements on a simpler musical task: *accelerando/decelerando* on one single note.

3 Method

We used a Vicon System 460 optical motion capture system to measure the arm and bow movements. Six M2 cameras were placed around the instrumentalists providing a spatial resolution below 1mm with a frame rate of 500Hz. Markers were placed on the players' upper body, following the standard marker placement in the Vicon Plug-in Gait [14]. Six markers were placed on the instrument, four for the table and two for the strings. Three markers were placed on the bow. With this setup, the movement of the bow can be computed relatively to the instrument. The position of the contact point between the bow and the strings is calculated and is used as the center of an instrument-based frame of reference.

Bow pressure on string was measured with a custom sensor designed at Ircam [15], with a $\pm 3\%$ error. Bow pressure data were recorded separately from motion capture data. To ensure a post-recording synchronization between both sets of data, the sound was recorded simultaneously with each sensing system: we use the arg-maximum of the cross-correlation between the audio signal envelopes to align both sets of data.

Two students from McGill Schulich School of Music were recorded playing an *accelerando*, from medium paced *Détaché* to a "as fast as possible", tied with a *decelerando* back to medium paced *Détaché*. Musicians were asked to stay on a fixed note. One McGill student played the violin, the other student played the viola. Both McGill students were advanced level with more than ten years of instrument practice.

4 Results and Discussion

The presentation of results is structured as follows: first, we study bow movement and focus on a change in bowing gestures found on the velocity and acceleration profiles during an *accelerando/decelerando*. Second, we present the results relative to the arm joint angles providing additional insights on this change. Last, we show results of the sound characteristics at the moment of the bowing change.

4.1 Change in bowing gestures

Bow movements: Figure 1 shows the position, velocity and acceleration of one point of the bow, for the viola player. For clarity, the bow stroke frequency is also plotted, showing the *accelerando/decelerando*. Bow stroke frequency is defined as the inverse of a stroke duration and is computed as the inverse of the time separating two successive zero crossings of the bow velocity curve. Due to the physics of bowed strings, the amplitude variations of velocity and acceleration are bounded within an interval that guarantees the production of an acceptable sound [16]. There is no such constrain on the distance, and thus tempo variation is achieved by reducing the length of bow, as already noticed in reference [12]. Biomechanics also imposes this reduction: the combination fast tempo - long strokes is indeed very difficult to achieve. Figure 1 shows that the absolute value of the acceleration amplitude remains relatively constant, while the observed dramatic decrease of the position amplitude is directly correlated with the increase of bow stroke frequency.

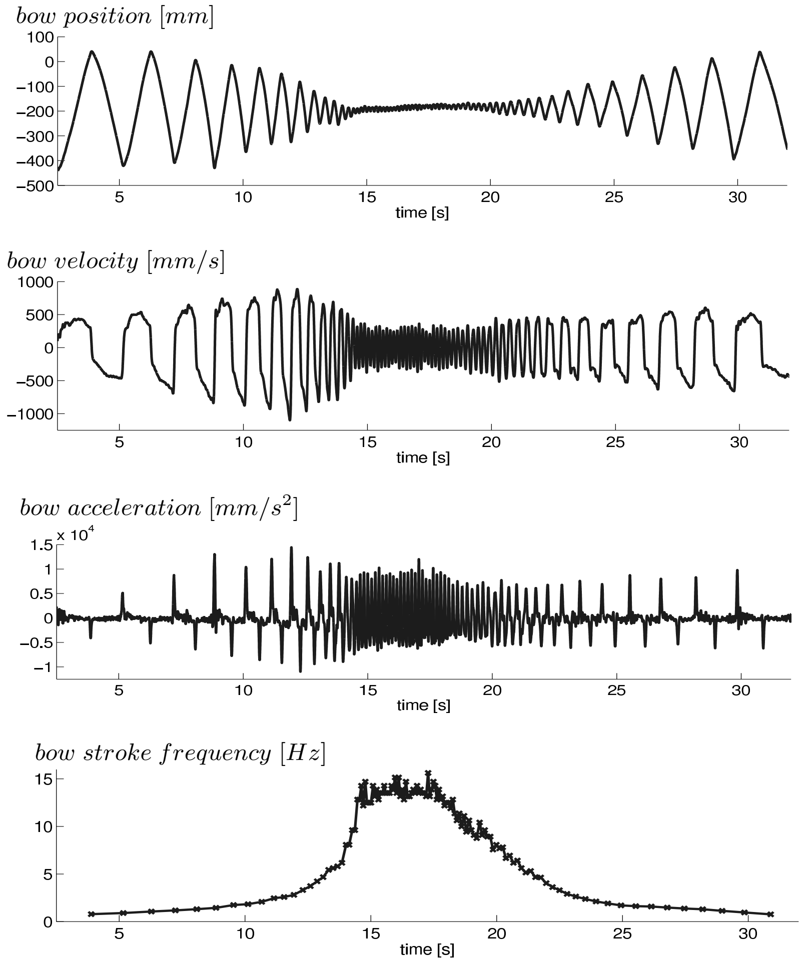

Fig. 1. From top to bottom: bow position, velocity, acceleration and bow stroke frequency for the *accelerando / decelerando* performed by the viola player.

However, a zoomed view of bow velocity and bow acceleration reveals an interesting profile change in the middle part of the *accelerando / decelerando*. Figure 2 shows the two players' bow dynamics at this moment. The profile change is observable for both players. Two different patterns are clearly visible on the graphs: the acceleration profile drastically changes becoming smoother at times

$t = 14s$ for the viola and $t = 11s$ for the violin. For both players, the reverse change occurs during the *decelerando*.

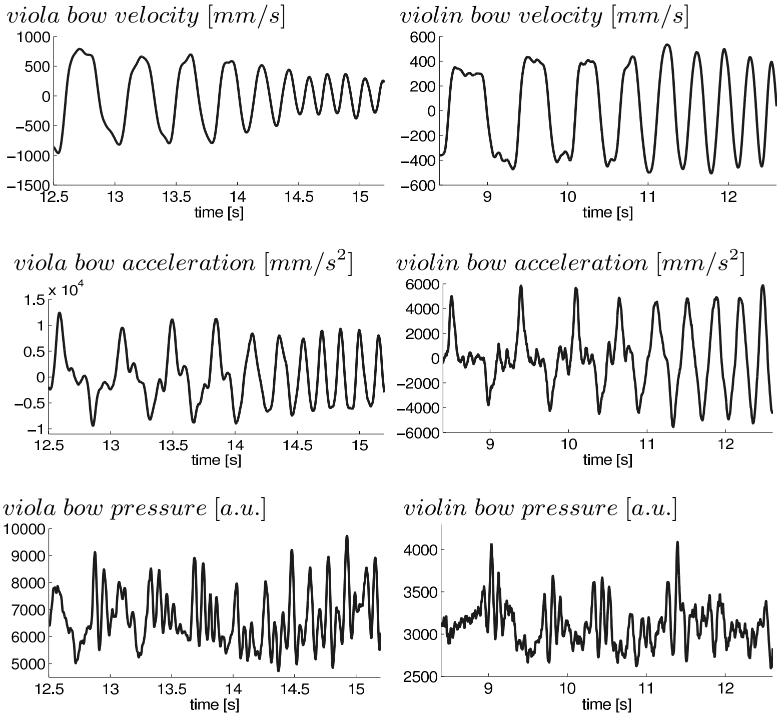

Fig. 2. From top to bottom: bow velocity, bow acceleration and bow pressure on strings. For both instrumentalists, a clear change in profile occurs for bow velocity and acceleration but not for bow pressure.

These two patterns allow us to section the *accelerando / decelerando* in three parts. In the first and third parts, denoted by $C1$ and $C3$, the velocity is close to a square signal, the acceleration profile is characterized by well defined short positive and negative peaks. Between these peaks, other smaller peaks are observable. In the second part, denoted $C2$, the velocity and acceleration profiles are smooth and close to sinusoidal. It is worth to notice that the change in bowing gesture is abrupt: no intermediate shape can be observed in the acceleration profile in Figure 2. It is also interesting to observe that no obvious, concomitant change occurs in the profile of bow pressure.

Profile characterization: To quantitatively characterize this profile change, we perform a sinus non-linear fit on bow velocity. Bow velocity is segmented in individual strokes. Each segment is resampled to a fixed number of points:

we chose 600 points, i.e. the length of the longest stroke in the measurements. Each segment is fitted to half period of a sinus fitting function, that allows for variable amplitude and phase, but with a fixed frequency. The estimation of the amplitude and phase parameters is performed with a non-linear least square regression. The mean square $fit\ error$ therefore provides a measurement of the profile change.

Figure 3 shows the $fit\ error$ parameter for the whole *accelerando* and *decelerando*. We can see a minimum plateau in the middle part for both players. Also, the value of the *error* is drastically higher at the beginning and at the end. This illustrates the change in profile observed in the previous section.

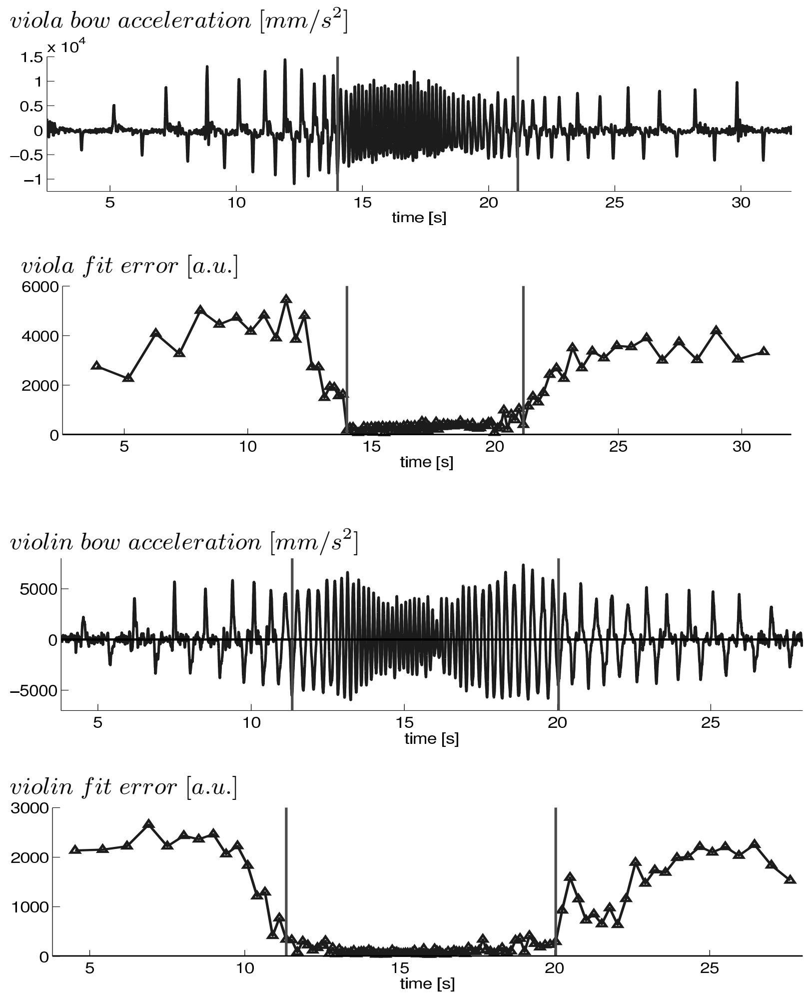

Fig. 3. Bow acceleration and the sinusoid $fit\ error$. The vertical bars were computed with a threshold based on $fit\ error$ values.

In these figures, we can delimitate the $C1$, $C2$ and $C3$ parts by applying a threshold on the fit $error$ parameter as shown by vertical bars in Figure 3. The profile changes in bow velocity and acceleration as seen in Figure 2 correspond approximately to a threshold of $560[a.u.]$ (value determined empirically).

Figure 4 plots the fit $error$ along with the strokes period, defined as the time interval between up and down bows. For both players, we can see that while the period decreases and increases in a linear way, the fit $error$ abruptly shifts from high to minimum values. This endorses our previous observation of abrupt transitions between the three parts $C1$, $C2$ and $C3$.

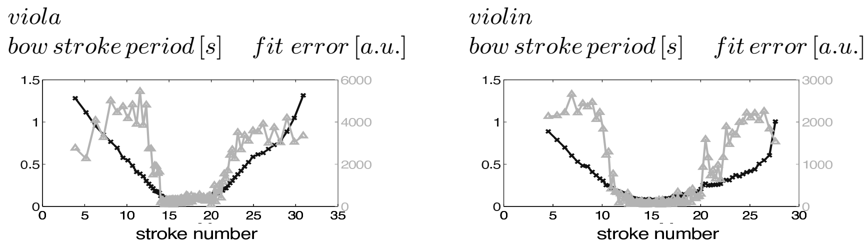

Fig. 4. In light color, the fit $error$ and in dark color, the bow stroke period. While the period decreases and increases in a linear way, the fit $error$ abruptly shifts from high to minimum values

We can also observe an hysteresis between the *accelerando* and the *decelerando*: the transition $C2 \rightarrow C3$ takes more time than $C1 \rightarrow C2$ for the two players. Moreover, we can notice that the frequency at which velocity profiles change is different between the two players. For the violin player, the $C2$ part comes early in the *accelerando*, at $f_{shift:C1\rightarrow C2} = 7Hz$, and the bowing frequency keeps on increasing up to $f_{max} = 15Hz$. On the contrary, for the viola player the $C2$ part coincides with the *accelerando* climax, at $f_{shift:C1\rightarrow C2} = f_{max} = 14Hz$. We cannot at this point know whether this difference is a function of the player or the instrument. More violin and viola players need to be considered to determine the typical frequencies for this profile change and their dependence on the instrument and the players' expertise.

Arm angles: Bow movements result from the coordination of the upper arm, forearm and hand. The analysis of arm joint angles can therefore give further insights to the observed change in bowing gesture, described in the previous section. From the motion capture data, we computed the elbow angle, i.e. the angle between the upper arm and the forearm segments, and the wrist angle, i.e. the angle formed by the forearm and the hand. We therefore consider the wrist and elbow angles, main contributors to the bowing movement, in a periodic flexion-extension movement.

The angle derivatives provide interesting information. Figure 5 plots the second derivative of the elbow angle. First, contrary to bow movement, arm movement shows major differences between the two players, as shown on Figure 5. This is explained by the large number of degrees of freedom in the arm. These differences actually express the players' personal bowing technique. However, for both players, we can notice changes at the transition time we determined from bow movements ($C1 \rightarrow C2$ and $C2 \rightarrow C3$). In Figure 5, we can see that similarly to bow acceleration, the profile of the second derivative of the elbow angle shows a dramatic change for both players ($t = 14s$ and $t = 11s$): it becomes smoother and almost sinusoidal.

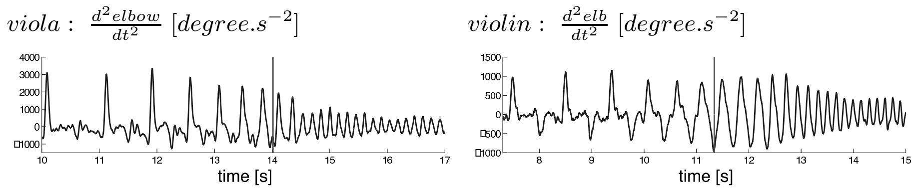

Fig. 5. Second derivative of the elbow angle. The vertical lines indicate the transition $C1 \rightarrow C2$. Similarly to bow acceleration, the profile of the second derivative of the elbow angle shows a dramatic change for both players.

Moreover, three additional parts can be identified in the arm movement from the analysis of joints' relative phases. The first derivates for the wrist and elbow angles are plotted on Figure 6. Indeed, during the $C2$ part previously defined, we can see another clear change occuring at the climax of the *accelerando*: for the violin player, the wrist and elbow curves first are in anti-phase at $t = 12s$, suddenly shift to in-phase at $t = 13.2s$ and gradually shift back to anti-phase at $t = 19.2s$. This change occurs when the bowing frequency is the highest. A similar but less obvious change also occurs for the viola (changes at $t = 18.8s$ and $t = 22.2s$). For the viola player, the in-phase / anti-phase transition occurs in the reverse way, i.e. first in-phase, then anti-phase.

These phase transitions indicate a possible reorganisation of within-limb coordinations such as described in [5], under the influence of increasing bowing frequency. Additional data from more players will bring a further characterization of this observation. It is also interesting to note that this change in joints' relative phase does not have a clear influence on the dynamics of the bow.

4.2 Audio comparison of the two bowing gestures

In reference [3], we reported the relationships between bow acceleration curves and bowing techniques that correspond to specific sound characteristics. We particularly stressed the gesture-sound continuity between the different bowing techniques. In the previous sections, we identified different bowing gestures for

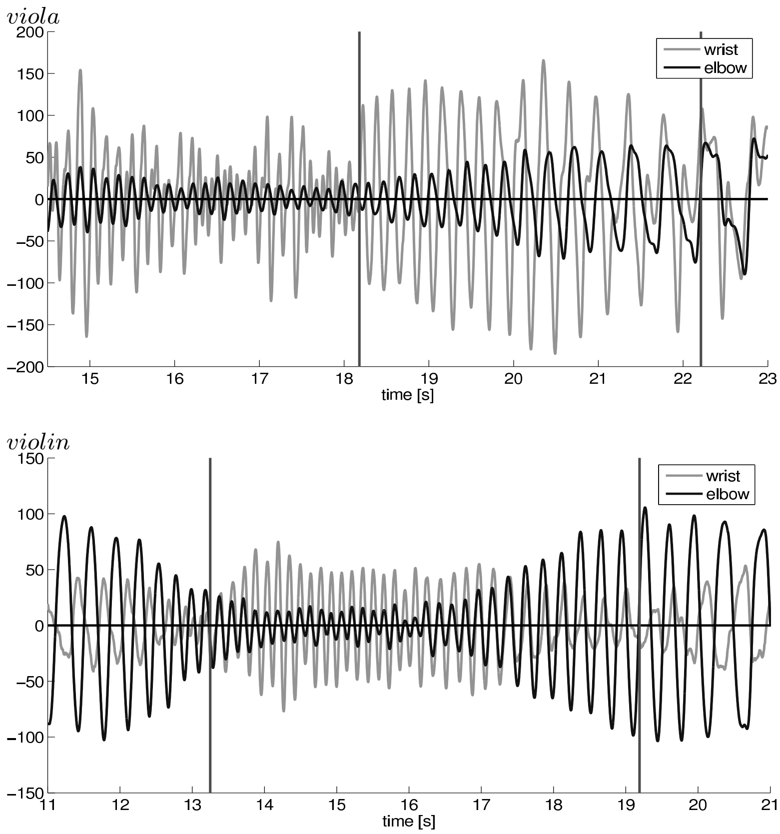

Fig. 6. First derivatives of elbow and wrist angles. Vertical bars indicate changes in the joints' relative phase.

slow and fast bowing with a brutal change between the two. We now investigate the effect of this change on the produced sound.

Interestingly, very few differences can be heard in spite of the drastic change previously described. This observation is supported by an audio spectrum comparison: for both players, there are indeed small differences in the spectra at the transitions ($C1 \rightarrow C2$ and $C2 \rightarrow C3$), as shown on Figure 7 for the viola player. We can see on top the mean audio spectrum $S1$ over the three strokes before

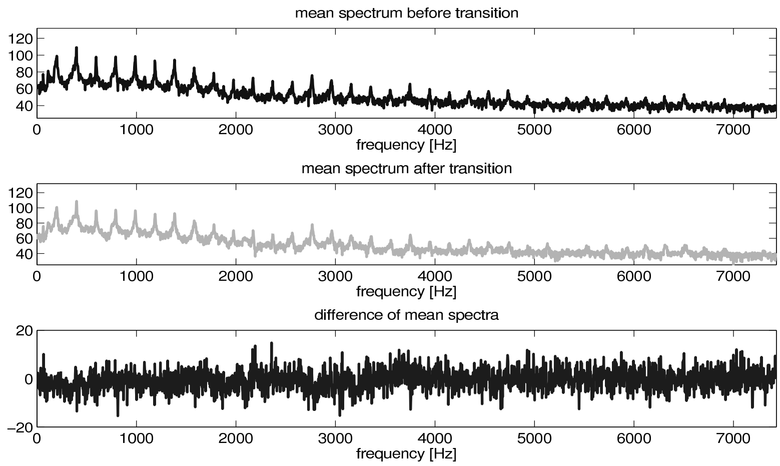

Fig. 7. Audio spectrum comparison for the viola player. Top: before $C1 \rightarrow C2$, Middle: after $C1 \rightarrow C2$, Bottom: spectrum difference

transition $C1 \rightarrow C2$, in the middle the mean audio spectrum $S2$ over the three strokes after the same transition, and at the bottom the difference between the two spectra ($S1 - S2$). We can graphically see that the two spectra have similar peaks in frequencies and amplitudes. This is confirmed with the difference between the two spectra: mean of $1dB$ with a standard deviation of $4dB$. However, it is worth to note that the difference is not uniform among the frequencies but slightly more important in the medium range, i.e. between $100Hz$ and $600Hz$. The spectral peaks having similar amplitudes, this is due to a difference in the noise level, which is lower in $C1$ than in $C2$. The origin of this last point will be further investigated with the help of physical models of bowed strings.

Further studies will also help to determine whether the sound similarities are actually due to an active, conscious or unconscious control of the musicians.

5 Conclusion and future directions

We present in this paper a study on the use of different bowing gestures by a violin player and a viola player to achieve different bow stroke frequencies. From the analysis of bow movement in an *accelerando/decelerando*, we showed the existence of two profiles in bow velocity and acceleration, therefore defining two bowing gestures. With a profile characterization based on a sinus non-linear fit, we noticed that the transition from one gesture to the other is abrupt with an hysteresis effect.

The study of arm joint angles also indicated the possible existence of a within-limb change of coordination for very fast bow strokes (15 Hz). In the case of the violin player, the elbow and the wrist first start in out-of-phase and shift to in-phase to achieve the fastest part of the *accelerando/decelerando*.

In the recorded performances of *accelerando/decelerando*, we could therefore clearly identify four parts in the players' movements: a square-shaped bow velocity, a sinus-shaped velocity with two possible arm coordinations, and a square-shaped bow velocity. Further studies must be performed to clarify the generalities of our findings.

Besides, an audio spectrum analysis does not reveal a clear concomitant change to the drastic change in bow velocity profiles. This might be due to the players being sufficiently experienced to smooth out the effects of changing bowing strategy. To test this hypothesis, new experiments with students of various levels, including beginners must be carried out. We can also hypothesize that the change in bowing gesture has an effect on finer timbre aspects like e.g. transitions between notes. These non obvious correspondances between gesture and sound and especially their evolutive aspect open interesting questions for the control of electronic sounds.

6 Acknowledgements

Nicolas Rasamimanana gratefully thanks funds from the Centre de Collaboration Interuniversitaire Franco Québécois. Thanks to Matthias Demoucron for his help and for lending us the pressure sensor he developed. We thank Florence Baschet, Christophe Desjardins, Serge Lemouton, Norbert Schnell and René Caussé for contributions, discussions and support.

This work was partly founded by the european project i-Maestro IST-026883. We also acknowledge the support of the project CONSONNES funded by the ANR (Agence Nationale de la Recherche, France).

The second and third authors are partially funded by the Natural Sciences and Engineering Council of Canada (Discovery and Special Research Opportunity grants) and by the Ministry of Economic Development of Quebec (Programme de soutien aux initiatives internationales de recherche et d'innovation). Thanks to support from the 6th Framework Project ENACTIVE Interfaces.

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