INTRODUCTION

A certain range of bow control parameters, dependent on played string and fingering position, is available to a string player. To obtain a sound of good quality, the combination of bow velocity, bow-bridge distance and bow force is required to satisfy the conditions for creating steady-state Helmholtz motion in the bowed string. The limits for tone production were described by Schelleng [1] who defined playable regions (known as Schelleng diagrams) by measuring bow force versus bow-bridge distance at fixed bow velocities (using a bowing machine).

Askenfelt [2, 3] was the first to extract bowing parameters from violin recordings using a thin resistance wire placed among the bow hair and four strain gauges mounted at the frog and tip of the bow. He analysed the use of the main bowing parameters (bow velocity, bow-bridge distance and bow force), registered from two violin players, depending on note duration, dynamic level and bowing technique. The recordings were made using the same violin and the same adapted bow. Aiming to extract typical values that occur in violin playing, he also reported on individual strategies in the use of the parameters. His findings were consistent with those of Schelleng. He confirmed that the bow velocity and the bow-bridge distance are the main player controls of the sound level. The bow force, although increasing with increasing dynamics (to adjust to higher bow velocities), does not contribute to the amplitude of sound. It mainly regulates the harmonic content, along with the bow-bridge distance.

The coordination and control of bowing parameters in violin and viola performance was studied by Schoonderwaldt [4]. Using optical motion capture combined with sensors [5], he recorded bow velocity, bow-bridge distance and bow force of three violin and three viola players in various settings, changing dynamic levels and note durations. The data were collected using the same instrument and bow combinations. He chose sound level and spectral centroid as sound features for investigating the relation between main bowing parameters and acoustic features of violin and viola sounds.

Little attention has been given to the use of bowing controls in cello performance. Sensor-based devices such as Hypercello [6] or cello adjusted Hyperbow [7]-[8] were mainly designed for interactive performance practice. The findings from violin case studies apply to cello as bowing technique principles are the same. However, considering both instruments, there has been no exhaustive research on how string players adjust their bowing technique to control the timbre of different instruments (playing two different violins for example) and maintain a desired quality of tone. In this study we aim to investigate the relationship between the bowing parameters in cello playing and spectral features of the sound produced showing different ways of adapting to the conditions of two instruments.

EXPERIMENTS

For this purpose bowing gestures and music samples from six advanced cellists were recorded on two cellos, both of a good luthier class, using the same high quality bow. The cellists were asked to perform a 3-octave D-major scale played upwards and downwards using identical fingering and bowing indications (43 notes in total, the pitch range D2–D5 corresponding to the frequencies 73.4–587.3 Hz) in two articulation variants: 4 notes played *legato* with the whole bow at tempo ♩ = 80 bpm (further as *scale1*), and a combination of 2 notes *legato* and 2 notes *détaché* played with the lower 2/3 part of the bow at tempo ♩ = 160 bpm (further as *scale2*). Tempo was given to the players before the start and during each session using a metronome light signal. The average note length at tempo 80 bpm and 160 bpm was 0.8 s and 0.34 s respectively. Both, bowing gestures and audio signals were registered via a dedicated sensing-recording system.

Data Acquisition

The motion tracking and audio capturing system (fully described in [9] and [10]) was designed for acquiring three data streams: bowing motion coordinates from sensors, an audio signal from a bridge pick-up, and, in addition, load cell values during a bow force calibration procedure. The bowing motion tracker was built on the *Polhemus Liberty* commercial unit, a 6DOF tracking system based on electromagnetic field sensing. The sensor data was captured at 240 Hz sampling rate and synchronised via a PC unit with the audio signal from the bridge pick-up. This signal is of special importance; being close to that of string vibration it reflects the spectral content of the sound source not affected by the resonances of the cello body. However this is the overall sound that is controlled by the player, the bridge pick-up signal gives a more direct measure of his/her actions in terms of bowing controls and resulting instantaneous changes in spectral characteristics of the produced sound.

The third component of the system was developed to measure bow force data acquired by means of a load cell, so that bow pressing force can be estimated. The load cell values were calibrated and translated into Newton units. As opposed to acquisition methods based on strain gauges mounted on the bow (as applied in [9], for example), an alternative method of bow force estimation has been proposed that calculates bow force using only sensor data. In the modelling phase, the method takes the bow-string distance as a simplified physical model of the hair ribbon and string deflection under bow pressing force (so called *pseudo-force*), together with the bow position and tilt (all captured in the force calibration procedure). Based on the three parameters, a regression model of the respective load cell values was built using the Random Forests technique. In the recordings, where it was not feasible to acquire load cell measurements, the bow force was estimated by means of the regression model.

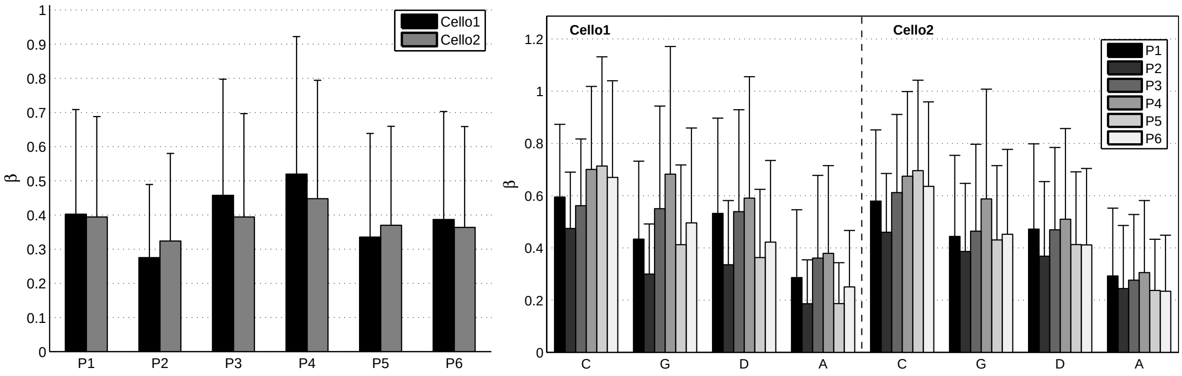
Gesture and Audio Data Processing

From acquired bowing motion coordinates a set of bowing controls was computed (definitions and derivation methods described in [9]). The bowing controls included: (i) bow-bridge distance relative to the string length and fingering position (β), (ii) bow transverse velocity (v_B), (iii) estimated bow pressing force (F_B), (iv) estimated string being played (*string*), (v) bow transversal position (x_B), and (vi) bow tilt (*tilt*). The computed bowing parameters and respective pick-up audio signals were segmented into notes using a semi-automatic procedure.

For spectral analysis, timbral features such as harmonic spectral centroid (f_c), harmonic spectral deviation (HSD) and harmonic spectral variation (HSV) were initially investigated as descriptors related to the the static and time-varying spectral content respectively. They have been identified by a number of perceptual studies as capable to characterise tones from different musical instruments. Of our particular interest was if those features can facilitate differentiating performers playing the same instrument [11] and as such, to be directly related to the performers' bowing controls. The descriptors were computed using the *Timbre Toolbox* [12] and its implementation of a harmonic sinusoidal model of the audio signal.

RESULTS AND DISCUSSION

For a comparative analysis of the players the bowing control parameters and audio features were calculated on the sustained parts of notes, excluding first 200 ms of the transition and attack portions in *scale1* and 100 ms in *scale2* respectively [4]. To summarise sequences of the parameters independently from the varying lengths of notes, mean and standard deviation values across notes were first calculated (median values for audio features) and subsequently averaged across strings and cellos.



(a) (b)

FIGURE 1: *Scale1* – bow-bridge distance (β) per performer on *Cello1* and *Cello2*. The average and standard deviation values: (a) across the whole scale; (b) across strings.

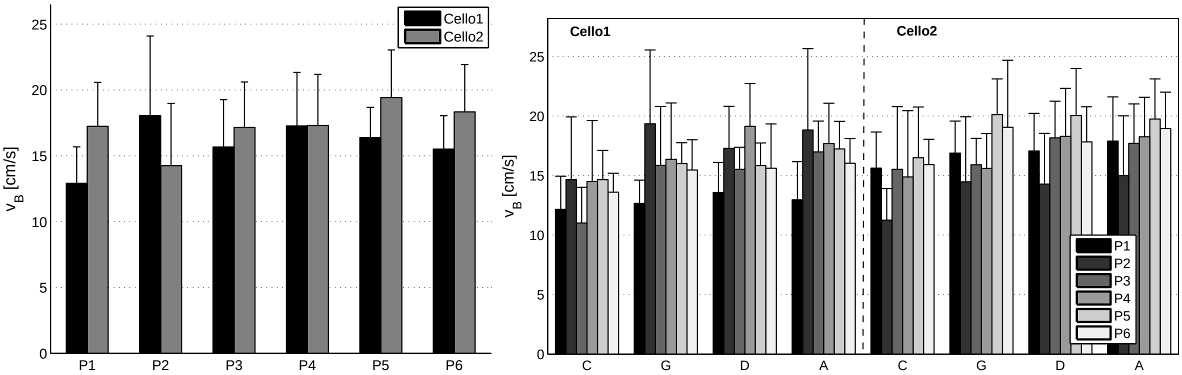


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FIGURE 2: *Scale1* – bow velocity (v_B) per performer on *Cello1* and *Cello2*. The average and standard deviation values: (a) across the whole scale; (b) across strings.

Figures 1–2 show the averages of the bow-bridge distance (β) and bow velocity per player in *scale1*. The average absolute bow-bridge distance observed across the players and cellos was 5.89 cm (0.39) with the minimum value of 2.43 cm (0.05) and maximum value of 11.24 cm (1.58). Evident variations in the use of this control between the cellists show how they adjust to different strings and instruments. While performers P1 and P6 use a similar bow-bridge distance on both cellos, performers P3 and P4 decrease the distance about 1 cm on *Cello2* in opposition to performers P2 and P5 who moved with the bow about 1 cm closer to the fingerboard. The average bow-bridge distance per player is presented in Table 1.

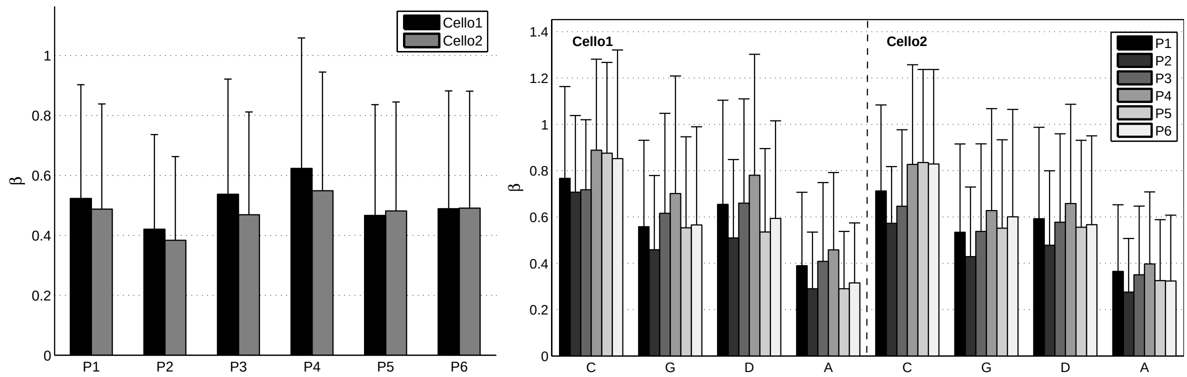
The observed general trend of reducing bow-bridge distance on the higher strings comes in agreement with adapting to a change in stiffness between the strings and in the fact of increasing pitch towards the top of the scale and subsequently shortening the actual length of the played string in the higher finger positions (especially on string A). Figure 1(b) indicates individual strategies across the strings showing consistent reduction of the parameter range on *Cello2* (3.93 cm in comparison with 5.72 cm on *Cello1*). High standard deviation values of the parameter also illustrate its strong variability between consecutive notes of the scale as the control is being adjusted to the string and the string length changes.

Bow velocity is directly correlated with the performance tempo. This explains outlying values of performer P1 (on *Cello1*) and performer P2 (on *Cello2*) who played a bit slower. The average bow velocity across the players and cellos was 16.62 cm/s with the minimum and maximum values at 6.14 and 32.39 respectively. The individual mean values are shown in Table 1. On average, the players used higher velocity on *Cello2* (17.28 cm/s) compared to 15.96 cm/s on *Cello1*. A general trend to play with higher velocities on the higher strings (see Fig. 2(b)) is a natural compensation for the reduced bow-bridge distance due to changes in string stiffness and fingering position. Regardless of the common tendency, some individual strategies in the use of this control were observed depending on string and cello (comparing players P4 or P5 for example).

TABLE 1: The average bowing parameters per performer across two cellos.

Parameter	Excerpt	P1	P2	P3	P4	P5	P6
bb_dist [cm]	*Scale1*	6.32	4.54	6.51	7.35	5.27	5.37
	Scale2	8.02	6.09	7.79	9.15	7.24	7.08
v_B [cm/s]	*Scale1*	15.07	16.15	16.40	17.28	17.90	16.92
	Scale2	39.31	43.83	43.45	39.32	39.78	37.19
F_B [a.u.]	*Scale1*	0.91	0.85	0.78	1.01	0.67	0.75

Figures 3–4 show the averages of the bow-bridge distance (β) and bow velocity per player in *scale2*. Generally, both bowing controls increased due to higher tempo (160 bpm) which agrees with results reported in [3] and [4]. The observed absolute bow-bridge distance was 7.56 cm (0.49) on average, with the minimum and maximum values equal to 3.16 and 11.88 cm (β = 0.78 and 1.61) respectively (for the individual values per player see Table 1). In general, the cellists played closer to the bridge on *Cello2* (7.39 cm compared to 7.73 cm on *Cello1*).

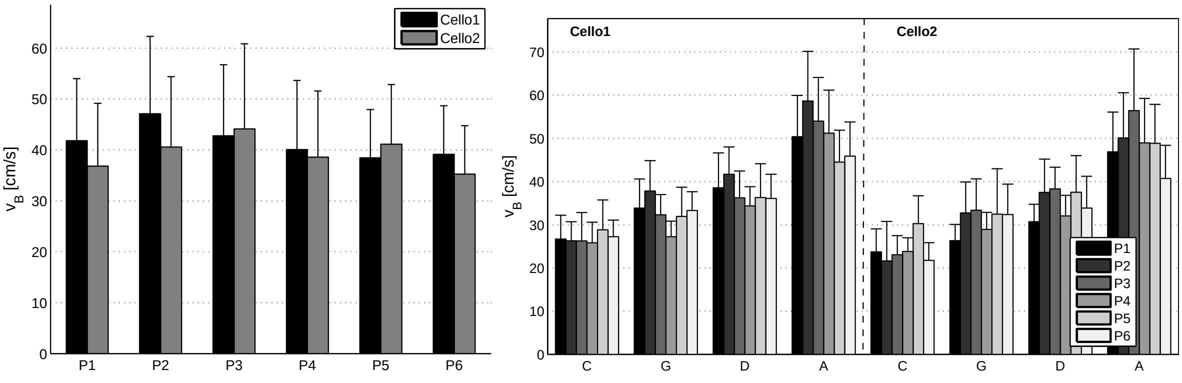


(a) (b)

FIGURE 3: *Scale2* – bow-bridge distance (β) per performer on *Cello1* and *Cello2*. The average values: (a) across the whole scale; (b) across strings.

Bow velocity increased with tempo up to 40.48 cm/s on average, with the minimum and maximum at 12.27 and 89.88 cm/s respectively. The individual values per player are shown in Table 1. As can be seen from Fig. 4(b), lower velocities were used on *Cello2* which came in agreement with playing in faster tempo at the smaller bow-bridge distances. One can notice an evidently stronger trend across the performers to play with higher velocities on higher strings, with a substantial change between strings D and A, up to 20 cm/s.

What clearly emerges from Figures 1(b) and 3(b) regarding bow-bridge distance is that cellists P2 and P4 were consistent in their choices of the control in comparison with others. In most of the cases, performer P2 played at the closest and performer P4 at the farthest distance to the bridge independently of the cello, string or tempo being played. What is more interesting, performer P2 played with the highest bow velocity (presumably to compensate the small bow-bridge distance) on *Cello1* but changed his tactic on *Cello2* by reducing the velocity while

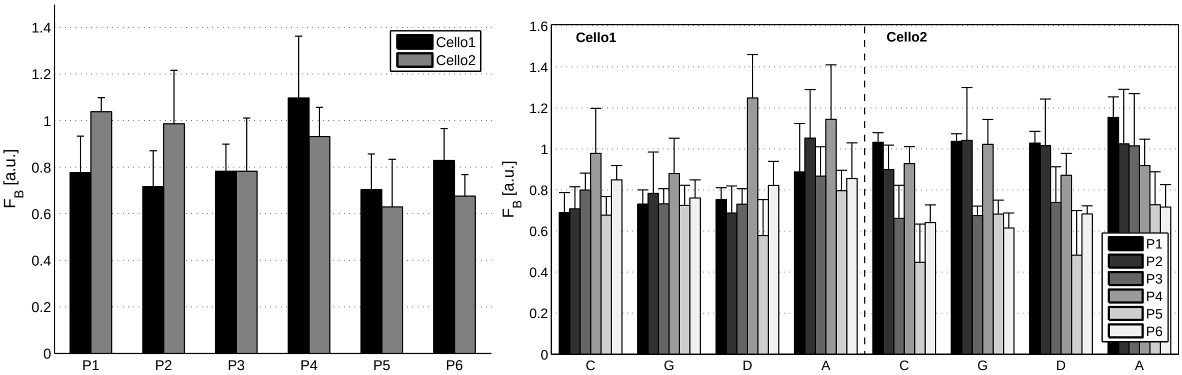


(a) (b)

FIGURE 4: *Scale2* – bow velocity (v_B) per performer on *Cello1* and *Cello2*. The average values: (a) across the whole scale; (b) across strings.

still playing closely to the bridge. On the other hand, performer P4 used the moderate bow velocity for most of the time while consistently playing far from the bridge. These two evident patterns must have been reflected in timbral characteristics of the players' tone.

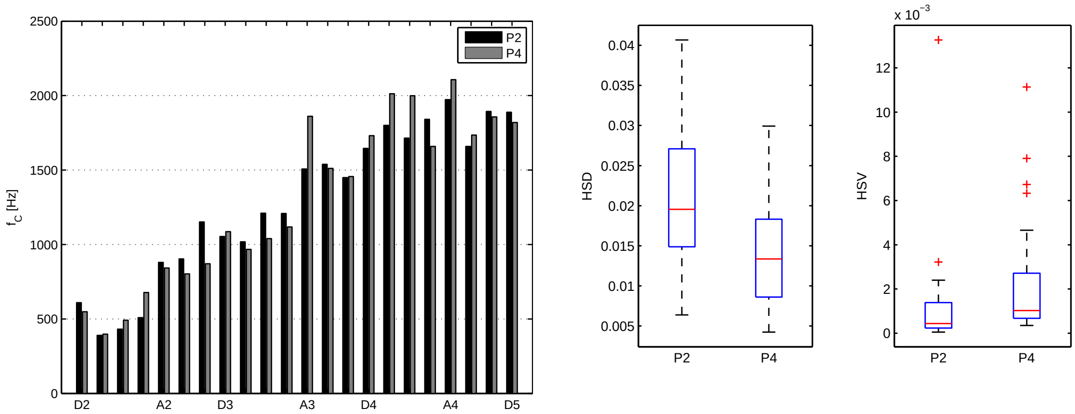
The bow force values estimated by means of random forests models can only be treated as a raw approximation of the control in real cello performance. The modelled parameter cannot be fully evaluated as, so far, there has been little research done in the use of bowing controls on cello and there are no real bow force measurements available. The estimated force is expressed in arbitrary units which can be related to the force units in Newtons. As depicted in Figure 5(b), variations in the use of bowing force between the players are more vivid on *Cello2*. Interestingly, on both instruments, performer P4 played on average with greater force than performer P3, P5 or P6 for example. This can be related to his/her manière of playing farther from the bridge as a way of maintaining a desired richness of tone. The observed bow force across the players was 0.82 [a.u] on *Cello1* comparing to 0.84 [a.u] on *Cello2*.



(a) (b)

FIGURE 5: *Scale1* – estimated bow force (F_B) per performer on *Cello1* and *Cello2*. The average values: (a) across the whole scale; (b) across strings.

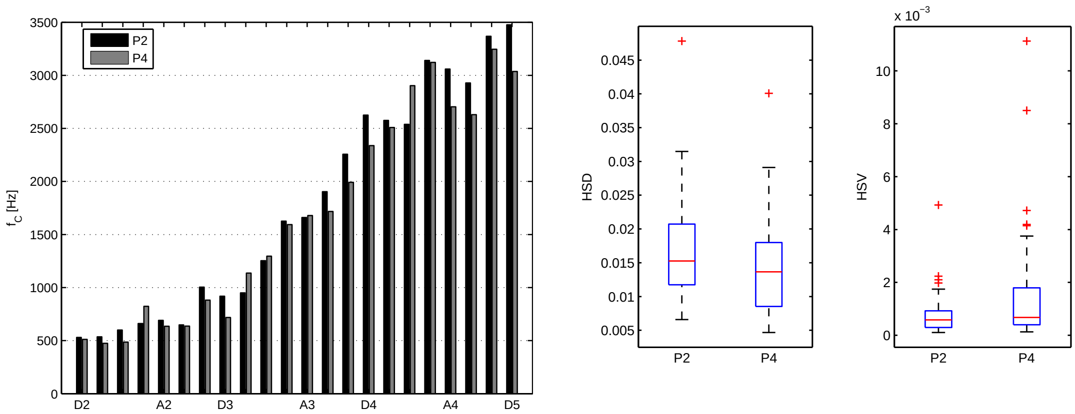
To investigate the relation between bowing controls and timbral features of the player tone, performers P2 and P4 were chosen for comparison as their individual patterns in the use of bowing parameters were more exhibited. Figures 6–7 show the computed audio descriptors (in *scale1*) which can represent a spectral characteristics of an instrument when looking at a general trend and indicate a performer effect when observing the descriptor variations. This



(a) (b)

FIGURE 6: *Scale1* – comparison of spectral features per performer P2 and P4 on *Cello1*. (a) Harmonic spectral centroid (f_c) – the median values per pitch. (b) Harmonic spectral deviation (HSD) and harmonic spectral variation (HSV) across the whole scale. The central red marks are the medians, the edges of the boxes are the 25th and 75th percentiles.

applies specifically to harmonic spectral centroid (Figures 6(a)–7(a)). Comparing the spectral slopes between two cellos, *Cello2* has on average higher spectral centroid (1688.7 Hz) as opposed to 1229.7 Hz of *Cello1*. By perceptual timbre studies spectral centroid has been related to the perceived brightness of sound. This means that *Cello2* should have a brighter timbre. According to the authors' subjective judgements *Cello2* indeed sounded lighter and brighter than *Cello1*, what was also confirmed in the performers' comments.



(a) (b)

FIGURE 7: *Scale1* – comparison of spectral features per performer P2 and P4 on *Cello2*. (a) Harmonic spectral centroid (f_c) – the median values per pitch. (b) Harmonic spectral deviation (HSD) and harmonic spectral variation (HSV) across the whole scale. The central red marks are the medians, the edges of the boxes are the 25th and 75th percentiles.

In general, the differences in spectral features between the two players were more pronounced on *Cello1*. For performer P2, higher values of spectral centroid and significantly higher spectral deviation than for performer P4 were observed. As reported in [11], spectral centroid and spectral deviation were positively correlated with perceptual attributes of tone such as "pinched", "harsh" and "strong". This can be related to the bowing controls performer P2 used on *Cello1*. Relatively the smallest bow-bridge distance, the highest velocity and the low bow force boosted higher harmonics in the spectrum causing the tone being "tensed". In opposition, performer P4 used relatively the highest bow-bridge distance, the high velocity and the highest bow force, and resulted sound can be described based on the timbral descriptors as less "bright" or "harsh".

Harmonic spectral variation is a measure of the variation in spectrum between the consecutive frames of the sound and can be affected by factors such as vibrato. In [11], a lower measure of variation was found to be more evident for the isolated tones which were played without vibrato. Although in our experiments the cellists were asked to perform the scales without vibrato, it might be a case that performer P4 unconsciously added a small amount and it has been reflected in HSV descriptor.

A bit different picture emerges from Figure 7 where the spectral features of the players P2 and P4 are compared on *Cello2*. Adapting to the physical conditions of the instrument they chose somewhat opposite strategies for dealing with its "brighter" timbre. Performer P2 used relatively the smallest bow-bridge distance, the smallest velocity and the high bow force while performer P4 played the farthest from the bridge with the high velocity and the high bow force. Resulting in rather similar timbral characteristics, performer P2 had still slightly higher spectral centroid and spectral deviation values and lower spectral variation to compare with performer P4.

CONCLUSIONS

Although the analysis presented above is far from being exhaustive, it provides a preliminary insight into a range of aspects that can be explored in cello performance using gestural information. While giving a brief comparative overview of the use of bowing controls on cello, it also shows individual strategies of two chosen players who adapted their bowing technique according to physical properties of instruments to control time-varying characteristics of the produced sound.

Future works will concentrate on identifying more salient spectral and spectro-temporal features capable to differentiate performers playing the same instrument with a special focus on features derived from the attack portions of sound samples. To explore to further extent the relation between bowing parameters and timbral descriptors, machine learning methods will be employed to map the two aspects of tone production and build respective models of the players.

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