IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 24, 2018, accepted June 18, 2018, date of publication July 13, 2018, date of current version August 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2856178

Assessing the Effects of a Primary Control Impairment on the Cellists' Bowing Gesture Inducing Harsh Sounds

JOCELYN ROZÉ, MITSUKO ARAMAKI, (Senior Member, IEEE), RICHARD KRONLAND-MARTINET, (Senior Member, IEEE), AND SØLVI YSTAD
Aix-Marseille Univ, CNRS, PRISM (Perception, Representations, Image, Sound, Music), Marseille, France

Corresponding author: Jocelyn Rozé (roze@prism.cnrs.fr)

This work was supported by the "Sonimove" Project under Grant ANR-14-CE24-0018.

ABSTRACT How do cellists' postural movements influence timbre quality during instrumental performance ? If this question seems complex at a first glance partly due to specific motor synergies for each musician, some principles of postural organization are believed to remain invariant while executing bowing gestures. In this paper, we reveal some of these common principles by investigating the effects of postural constraints on the mechanical behavior of the cellists' right arm, and consequently on the resulting bow velocity likely to cause timbre degradation, referred to as harshness ("*décharnement*" in French) by cellists. The kinematical data corresponding to the execution of a single note are collected through a motion capture system, and analyzed between two postural conditions of expressive playing: A normal one and a constrained one limiting chest and head displacements involved in the cellists' *primary control*. The comparison of relevant joint displacements and rotations between the two postural situations highlight the lack of coordination between spine torsion and shoulder opening as a main factor responsible for a tighter right arm gesture, potentially leading to a drop in bow velocity and consequently the production of harsh sounds.

INDEX TERMS Cellist, postural/instrumental gestures, acoustical timbre, musical expressivity.

I. INTRODUCTION

The investigation of musical gestures that are not directly related to the sound production is a research subject that has been given increased attention the last two decades. Often qualified of "accompanist" or *ancillary* to distinguish them from *instrumental* gestures directly responsible for the "effective" sound timbre [1], [2], these non-obvious movements seem however to play a role in the achievement of a solid musical technique [3], [4] as well as the reduction of musculoskeletal disorders or playing frustrations (Hoppenot,1981). A research methodology was defined to decode their musical significance through the prism of three main factors : physiological/ergonomic, structural and interpretative [5].

In this paper, we propose to investigate the connections between the cellists' ancillary movements and the quality of their timbre. This analysis is carried out during bow pulling gestures in a situation of *primary control* impairment, on one note frequently perceived as *harsh*. The concept of "primary control" has been defined in the area of experimental psychology as a central mechanism responsible for the whole body coordination and essentially involving the mobility between upper back, neck and head [6], [7]. "Harshness" (*décharnement* in French) refers to a specific kind of timbre degradation well known among cellists, which has been explored on the signal and perceptual sides within a previous study issued from the same context of primary control impairment [8]. As a follow-up of this acoustical study, we here aim to extract key body variables likely to explain alterations of the cellists' right arm control (holding the bow) and potentially leading to a harsh degradation of the perceived sound.

On the acoustical side, an analysis/synthesis approach by morphing was used to model the perceived harshness phenomenon. It consisted in creating continua between round and harsh sounds that were then perceptually evaluated by cellists [8]. Such a morphing technique already proved to be efficient for extracting acoustic features considered as main perceptual timbre attributes of an action recognition task [9]–[13]. Morphing has also been applied to signal parameters of violin performances (temporal and formantic envelope) in order to modify their expressive content in a gradual way [14]. Specific analysis techniques allow to infer the physical parameters responsible for the produced sound signal [15]. Such approaches can be used to develop models for gestural sound synthesis control [16], and bowed-string learning models able to generate sequences of spectral envelopes from continuous bowing and fingering controls [17]. Such models can be fed through platforms of multimodal archives combining data links between audio, motion capture and descriptor signals [18].

On the physiological side, the musicians' ancillary movements are sound-facilitating gestures, necessary to preserve and "support" the connection with their instrument [19]. This symbiosis process, so called embodiment [20], could be verified in many instrumental contexts: the importance of knee flexion for clarinetists [21] and trumpeters [22], the shoulder mobility for cellists [23] and harpists [24], or the anticipated elbow movements for pianists [25] themselves depending on more central body parts, as the shoulder, chest and head [26]. Physiological anticipation turns out to be the key factor of an improved coordination among the musicians: finger accelerations for clarinetists [27], stick velocity changes for percussionists [28], fingers speed/accuracy trade-off for pianists [29], or bimanual synchronization for violinists [30].

As a consequence of their anticipative aspect, ancillary movements intrinsically connect to the musical time flow and the phrasing structure. This mechanism, so called *coarticulation* [31], was demonstrated through reproducible ancillary patterns localized at key points of the score for pianists [32] or clarinetists [33]. For bowed-string instruments, it was shown that coarticulation patterns also change according to the type of bow stroke detached/legato [34]–[37]. Some studies investigated the effects of postural immobilizations on the musicians' sense of time flow: Wanderley revealed that clarinetists tend to unconsciously rush the performance when instructed to move as little as possible [21] and Rozé suggested that the cellists' sense of pulse is altered within rhythmically demanding passages under physical immobilization by the chest and the head [38].

Similar works in the speech area highlighted that an inhibition of non-verbal gestures altered the speech fluidity as well as intonation quality, which becomes more laborious and tense [39]. However, to our knowledge, no works proposed to explore the timbre quality produced by an instrument when the musician is submitted to targeted postural immobilizations: Wanderley revealed that clarinetists' acoustic signal looses its harmonic fluctuations when the instrument is immobilized by a mechanical apparatus [40]; and Rozé suggested that the cellists' timbre variations become more uniform and dull on specific passages under primary control immobilizations [38]. Further elements of such specific embodied cognition effects can be found in the pedagogical literature: the oboists' rib cage compression with the elbows might result in muffled sounds [41]; the violinist/instrument's close intimacy would transmit any body tightness to the sound quality [42]. Like a *domino toppling row* [43], the cellists' motor control may follow the same logic by encoding *significant energy forms* [44] within the produced sound from the ancillary movements of more central body parts (torso, head). A lack of *statesthesy* or postural sense [16], [45] might thus transfer to unsuitable bowing velocity/pressure parameters [46], resulting in incorrect "moving sonic forms" [47], i.e. harsh sounds.

This paper is divided into five parts: The first one presents an experimental protocol set up to investigate the cellists' sound and movement features when submitted to primary control limitations. The second part describes the effects of these limitations on the bow velocity parameter, related to the harshness phenomenon. The third and fourth parts analyze the coordination alterations between the trunk and the right arm in terms of joint displacements and rotations respectively. Finally, in the fifth part, a simple model of the key postural variables is built among cellists to explain the bow velocity changes.

II. EXPERIMENTAL PROTOCOL

The analyses presented in this study have been carried out from data collected within a large experiment, and designed to assess the influence of specific postural movements on the musical expressivity of cellists [38].

A. PARTICIPANTS

Seven cellists (4 males, 3 females) took part in the experiment. We chose musicians with high-level expertise, to ensure that any expressive degradations were due to postural constraints and not to technical weaknesses.

B. APPARATUS

The cellists' body movements were recorded using an eight-camera infrared motion capture system (of type Vicon 8),[1] as illustrated in Fig. 1. This system tracked the three-dimensional positions of 29 reflective markers positioned on the performers' body, and 9 additional markers placed on the cello and the bow at a frame rate of 125 Hz. The body markers were distributed according to the locations provided by the anatomical standard "Plug-in-Gait,"[2] and corresponding to natural human joints or salient bone parts (cf Sec. II-E).

Audio data were recorded by a microphone placed under the cello bridge (DPA 4096) and connected to a MOTU interface (Ultralite MIC3) sampled at 44.1 kHz. This microphone location allowed to capture the acoustical features within the sound signal at source, without being affected by potential reflections of the experimentation room. Audio and move-

---

[1] The Vicon 8 motion capture system used for the experiment was lent by the ISM (*Institut des Sciences du Mouvement)* of Marseille

[2] Vicon Motion Systems. Plug-in gait product guide. Oxford: Vicon Motion Systems, 2010, http://www.irc-web.co.jp/vicon_web/news_bn/PIGManualver1.pdf

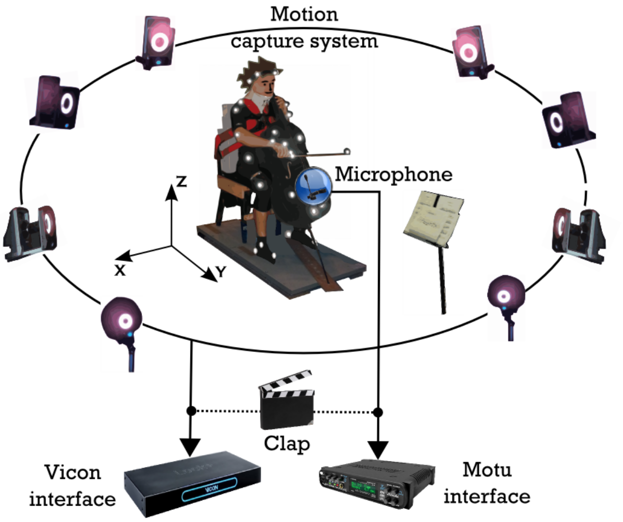


FIGURE 1. Experimental design : Motion capture system (VICON 8) and microphone (DPA 4096). A manual clap is used to synchronize movement and audio streams.

ment recordings were synchronized by means of a manual clap (cf Fig. 1) at the beginning of each recording.

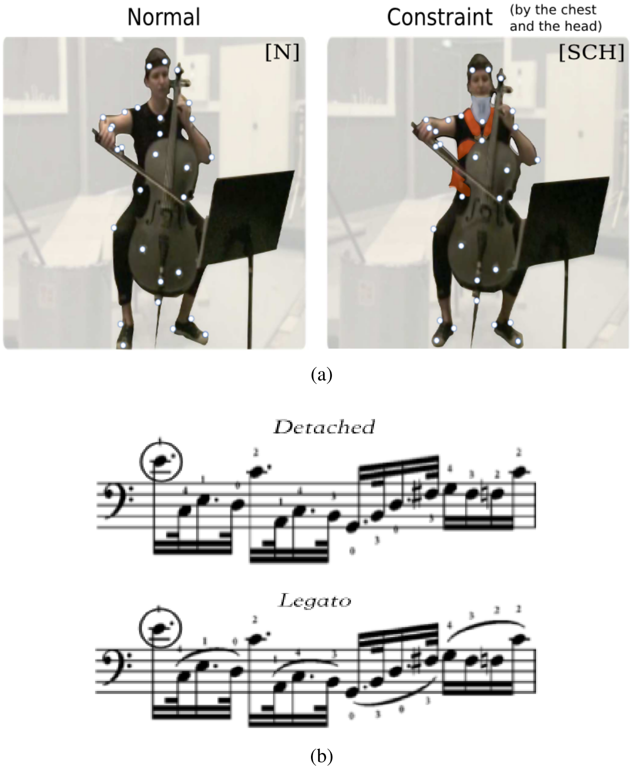
C. PROCEDURE

The cellists were asked to play a calibrated score in the most expressive way, at a slow tempo (45 bpm), for various conditions of postural immobilization and bow stroke types (detached/legato). In this paper, we focus on two opposite postural conditions, illustrated in Fig. 2(a) :

- *Normal condition* [N] : Natural play as in a performance context.
- *Static Chest and Head condition* [SCH]: Constrained situation in which both the chest and the head of the cellist are physically immobilized. More precisely, lateral (right/left) and sagittal (forward/backward) trunk displacements were restrained by attaching the cellist's torso to the back of the chair with a 5-point safety race harness. The head movements were limited by an adjusted neck collar.

D. NOTE SELECTION AND SOUND CORPUS

Among the score parts played by the cellists, one was assessed as particularly difficult to perform in the physical fully-constrained postural condition (cf Fig. 2(b)). Most of the interviewed cellists actually reported that in this context they had the impression of producing "tighter, tenser sounds" or "sounds lacking of depth and natural resonances", whatever the type of bowing stroke between the notes (detached/legato). A previous study confirmed these subjective alterations of the timbre quality by highlighting less spectral richness variations in the acoustic signal, especially between the first four notes of the 4^{th} part, when played in full postural immobilization context [38].

By thoroughly listening to the sound recordings, we identified the note that most consistently was affected by timbre degradation. This note corresponded to the first dotted sixteenth (pitch E3) of this score part and was frequently qualified as "harsh, shrill and whistling". Our current research focuses on the bow pulling movement associated to the selected E3 note, by comparing displacements and angular variations within the cellists' kinematic chain between a pair of round and harsh timbre of the note.

(a)

(b)

FIGURE 2. Experimental procedure. (a) Two opposite postural conditions. (b) Fourth part of the score with the selected note E3 (circled).

The motion selection is based on the corpus of ten sound pairs, already used in a previous acoustic study on the harshness phenomenon [8]. Each round/harsh pair was respectively extracted from the normal [N] and the fully-constrained [SCH] postural situations of the same cellist (for the same bow stroke type). A specific pitch-tracking algorithm was built and adapted from the MIR toolbox [48]–[50] for this extraction process of the E3 notes. From the listening tests which were performed, we selected eight out of ten pairs ranked by the subjects as the perceptually most salient in terms of harshness variations. It should be noted that these pairs are quasi-independent, since extracted from seven different cellists with only one repetition for a cellist.

E. MOTION DATA PREPROCESSING

The motion capture recording contains the raw spatial positions of the markers along successive temporal frames. For our analyzes, we built a *Dempster model* based on this marker set [51], and illustrated in Fig. 3(b). It consists in a simplified subset of the anatomical "Plug-in-Gait" marker set, and is

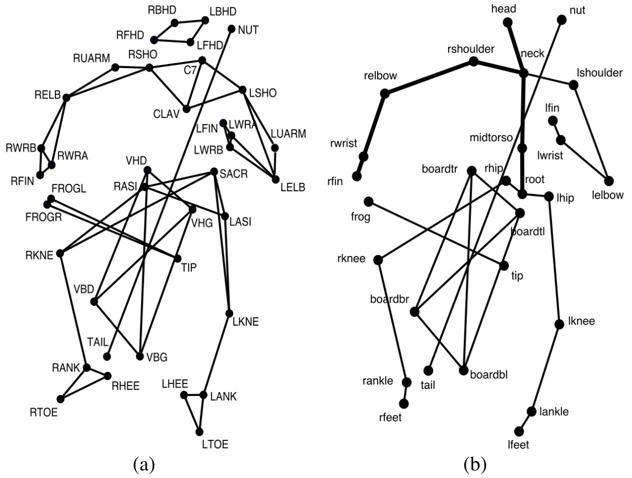


FIGURE 3. Conversion process from the initial "Plug-in-Gait" model (based on raw motion capture data) to the reduced "Dempster" (based on barycentric data computations). (a) "Plug-in-Gait" marker model. (b) "Dempster" marker model.

composed of 20 markers corresponding to the 20 main body joints. The conversion process from the "Plug-in-Gait" to the "Dempster" model was achieved by means of the MoCap Toolbox [52], according to barycentric computations of several raw marker positions described Tab. 1.

TABLE 1. Conversion table from the "Plug-in-Gait" markers to the "Dempster" markers of the segment chains (*ancillary and instrumental*). A Dempster marker can match a single Plug-in-Gait marker or be computed as the barycenter of several Plug-in-Gait markers (listed accordingly).

"Dempster" markers	"Plug-in-Gait" markers
Ancillary chain	
root	LASI-RASI-SACR
midtorso	CLAV-C7-LASI-RASI-SACR
neck	LSHO-RSHO-C7
head	LFHD-RFHD-RBHD-LBHD
Instrumental chain	
rshoulder	RSHO
relbow	RELB
rwrist	RWRA-RWRB
rfin	RFIN
frog	FROGL-FROGR
tip	TIP

Kinematic analyses conducted in this paper essentially rely on two body segment chains of the Dempster model (cf bold segments in Fig. 3(b)), and extracted for the eight round/harsh pairs of the sound corpus:

- *An* ***ancillary chain*** which matches the four trunk segments (abdomen, chest, neck, head) attached by the following joint markers : *root, midtorso, neck, head.*
- *An* ***instrumental chain*** which matches the four right arm segments (right shoulder, right upper arm, right lower arm, right hand) attached by the following joint markers: *rshoulder, relbow, rwrist, rfin*. This chain encompasses the bow *frog* and *tip* markers as well.

Based on the three-dimensional marker positions of these body segment chains, we here characterize the cellists' movements through two fundamental attributes: joint displacement and rotations. The aim of these two complementary approaches is to highlight the joint coordination mechanisms in relation to the instrumental bowing gesture directly producing the sound.

III. INFLUENCE OF THE INSTRUMENTAL GESTURE ON THE PERCEIVED HARSHNESS

If a harsh sound may potentially result from a lack of postural coordination, it has undoubtedly its origins within an incorrect combination of the bowing parameters responsible for the physical energy transfer to the instrument, i.e. the bow force and the velocity [46].

On the acoustical signal side, this harshness phenomenon is characterized by a more unstable Helmholtz motion (loss in synchronicity between signal transients), building up more slowly (weaker temporal attack slope), and correlated with a formantic shift toward higher order partials of the spectrum [8], [53], [54].

From the physical point of view, bowing machine experiments well demonstrated that an increase in energy in the upper partials of the sound is correlated with an increase in bow force and/or a decrease in bow velocity [46], [55], [56]. Related research also revealed that a loss in the temporal attack slope of the sound may be due to a weaker acceleration, or a slower bow velocity [57], [58]. Hence, according to previous works, we hypothesize that a harsh sound would be produced by a slower bow velocity.

A. GESTURE/SOUND DESCRIPTORS

1) BOW DESCRIPTOR

The bow velocity has been computed as an average - on the selected note - of the velocity vector norms for the bow "frog" marker (cf the Dempster model in Fig. 3(b)):

$$Bow\ velocity = \sqrt{\left(v_x^2 + v_y^2 + v_z^2\right)} \tag{1}$$

where the triplet (v_x, v_y, v_z) refers to the spatial coordinates of the bow frog velocity vector at a specific frame of the motion capture sequence. Each triplet of the velocity vector was obtained by a derivation process of the successive bow frog marker positions (x, y, z), based on the Savitzky-Golay algorithm [59]. We configured the Savitzky-Golay smoothing filter with a small regression window of five frames to keep enough details in the signal, and two-order polynomials to take into account the motion path curvatures.

2) HARSHNESS DESCRIPTOR

A perceived harshness descriptor was computed on the selected note by means of the regression model obtained in [8]:

$$Harshness = 0.29 \times MFCCratio - 0.36 \times ATS + 0.49 \times HSV \quad (2)$$

This model was built from subjective ratings of continuously harsher sounds. It is composed of a combination of three acoustic descriptors identified as the most relevant for the harshness perception:

- *MFCCratio* (ratio between MFCC coefficients c2 and c1): The associated weight (+0.29) reflects the emergence of a formantic area [60].
- *ATS* (Attack Time Slope): The associated weight (-0.36) reflects a slower attack [61].
- *HSV* (Harmonic Spectral Variation between adjacent frames): The associated weight (+0.49) reflects an increase of asynchrony between harmonics [62].

B. RESULTS

Bow and harshness descriptors (Eq. 1 and Eq. 2) have respectively been computed on the sound corpus of eight round/harsh pairs. This produced two samples of 8 × 2 values, one for each opposite postural condition: normal [N] and fully-constrained [SCH]. Fig. 4 presents the quartiles for the two descriptors for each postural condition. A paired two-tailed t-test performed on each descriptor revealed that for the [SCH] condition, the bow velocity was marginally lower ($t(7) = 2.22, p = 0.062$) and logically, that the harshness descriptor was significantly larger ($t(7) = -2.51^*$, $^*p < 0.05$) than for the [N] condition.

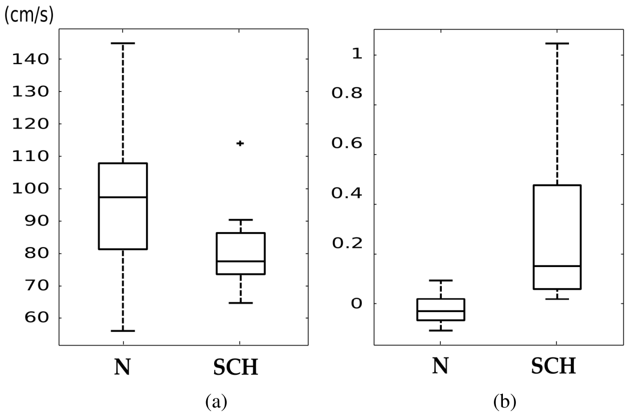


FIGURE 4. **Boxplots of the bow velocities (a) and harshness values (b) between the opposite postural conditions [N/SCH] of the eight round/harsh pairs. The central marks are the medians, the edges of the boxes are the 25th and 75th percentiles. (a) Bow velocity. (b) Harshness descriptor.**

Therefore, this suggests that the harsh sounds collected through a postural immobilization by the chest and the head result from a slower bow velocity. This result is also compliant with the pedagogical literature which suggests that if the cellists' *primary control* is reduced, they also loose an essential capacity of *bow breathing*, i.e. an expression of their full tone coloration range [7], [42]. This tendency of bowing gesture impairment should be further analyzed for a more detailed description of the motor organization, and the set up of potentially altered coordination strategy between the right arm joints.

IV. EFFECT OF PRIMARY CONTROL IMPAIRMENT ON THE RIGHT ARM JOINT DISPLACEMENTS

In this part, we investigate the coordination of the cellists' right arm motor control through two kinds of measurements: "absolute" or global joint displacements, and "relative" or local between-joint displacements. An immobilization of the musicians' primary control by a combination of chest and head constraints might actually alter these basic movement variables, likely to induce an insufficient bow velocity while playing the studied note, hereby creating the harshness phenomenon.

Human postural activity can be tracked through the kinematics revealing the evolution of body joints over time [63]. During the cellists' bow pulling movement studied here, these joint displacements are ensured by a selective reduction of their mechanical degrees of freedom within task-specific *synergies* or coordinative structures [64]. Postural constraints with harness and minerva devices reduce the natural joint degrees of freedom involved in the behavior of these functional muscle linkages.

A basic way to observe these effects on the movement construction may consist in computing the *Quantity of Movement* (QoM) of each articulation. Computations of joint movement amounts can be "absolute" to represent an overview of total traveled distances by the markers [26], [65], or "relative" to get more details on the movement distribution between each marker [66]–[68]. For the violinists, general marker velocities and absolute quantities of movement evolve accordingly [36]. Therefore, we hypothesize that a slower bow velocity responsible for a harsh sound may be induced from insufficient amounts of the displacements of the right arm joints.

A. AMOUNT OF JOINT DISPLACEMENTS

1) ABSOLUTE QUANTITY OF MOVEMENT

The absolute QoMs have been computed as the cumulative distances travelled by each joint on the selected E3 note. Considering one body joint, this represents the sum of the vector norms of all its inter-frames motions:

$$QoM = \sum_{f=2}^{N} ||\vec{u}_{f-1}^{f}|| \quad (3)$$

where $\vec{u}_{f-1}^{f}$ is the tridimensional motion vector of a joint between frames $f-1$ and f. This cumulative sum is computed on the N frames corresponding to the note duration for each of the ten Dempster model markers (cf Tab. 1): the four "ancillary chain" markers (*root, midtorso, neck, head*) and the six "instrumental chain" markers (*rshoulder, relbow, rwrist, rfin, frog, tip*).

2) RELATIVE QUANTITY OF MOVEMENT

The relative QoMs have been computed as the coefficients of a *Principal Component Analysis* (PCA) applied on the dataset of marker coordinates for the selected E3 note. The PCA technique actually reduces the dimensionality of this large initial dataset to a smaller dataset of principal components, defined by linear combinations of the centered original variables:

$$\rho = (U - \overline{U})\xi \qquad (4)$$

where $U - \overline{U}$ is the centered dataset of original variables, and ξ are the coefficients of linear combinations determined to maximize the intrinsic variance of U. The principal components ρ represent a *basis of factors*, i.e. the axes of a projective subspace in which the coordinates of U can be reexpressed as movement patterns (or *eigenmovements*). The PC projections U_m denote the new coordinates of U within this basis of M factors:

$$U_m = \overline{U} + \rho_m.\xi'_m \quad m \in [1, M] \qquad (5)$$

In our study, each dataset U subjected to PCA corresponded to a movement sequence composing the corpus. U contained a table storing the three-dimensional coordinates of the ten studied markers of Dempster model (cf Tab. 1) along the N motion capture frames of the note duration. A movement dataset thus consisted in a series of 30-component vectors (10 markers × 3 coordinates) of N motion capture frames. The PCA applied on each dataset computed M principal components ξ_m from the variance of the marker trajectories, corresponding to M specific *eigenmovements* of the sequence. In our context, these *eigenmovements* were returned as 30-component vectors, indicating the relative amount of joint displacements in the three spatial directions: X (medio-lateral or right/left axis), Y (antero-posterior or forward/backward axis), and Z (vertical axis).

B. RESULTS

1) ABSOLUTE JOINT DISPLACEMENTS

The absolute QoMs (Eq. 3) of the ten Dempster body joints have been computed on the motion vectors associated to the sound corpus. This produced two samples of 8 × 10 values, one for each opposite postural condition: normal [N] and fully-constrained [SCH]. From this dataset, we conducted two kinds of analyses:

a: MEAN QoMs

First, the ten QoM values were averaged for each sound, in order to observe global trends of joint displacements between [N] and [SCH] postural conditions. This reduced the dataset to two samples of eight mean QoM values, which distribution is illustrated in Fig. 5. A paired two-tailed t-test carried out between samples turned out to be significant ($t(7) = 2.43^{*}$, $^{*}p < 0.05$), with a lower mean QoM for the [SCH] condition. This result highlights that the cellists' primary control is important to ensure their right arm movement amplitudes. Hindering these postural adjustments might cause slower bow movements measured for the sample of harsh sounds (cf Fig. 4(a)).

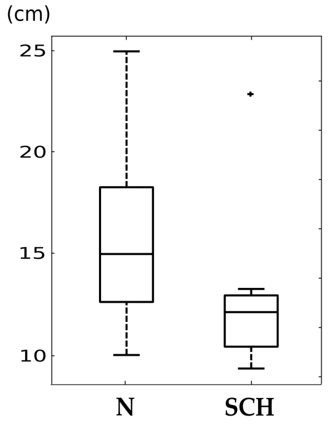


FIGURE 5. **Boxplots of the mean quantity of joint movement (QoMs) between the opposite postural conditions [N] and [SCH] of the eight round/harsh sound pairs. The central marks are the medians, the edges of the boxes are the 25th and 75th percentiles.**

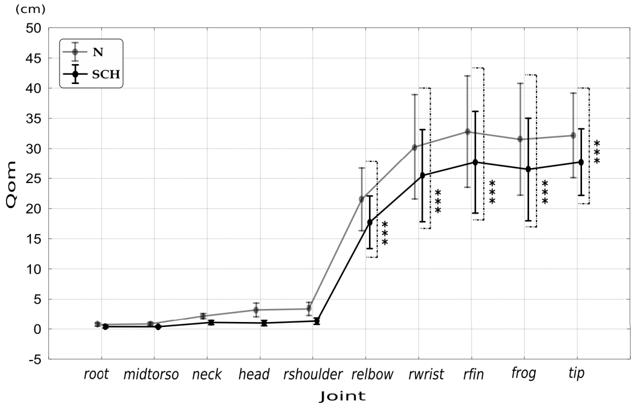
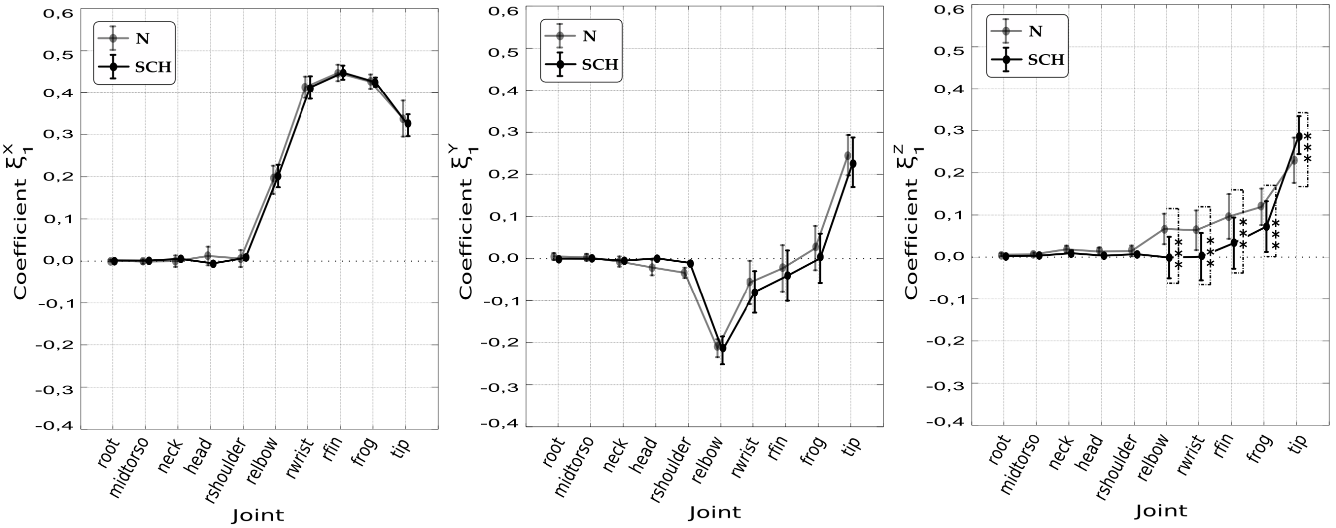


FIGURE 6. **Absolute joint displacements (QoMs) of the ten Dempster body joints computed on the corpus of eight round/harsh sound pairs. The significance of differences in joint QoMs between [N] and [SCH] is given by the p-value issued from post-hoc pair-wise comparisons (LSD) of repeated-measure MANOVAs: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.**

b: INDIVIDUAL QoMs

Second, the QoM values were averaged for each joint on the eight pairs, in order to get individual tendencies of joint displacements between [N] and [SCH]. It reduced the dataset to two samples of 10 mean QoM values, which repartition is illustrated in Fig. 6. We performed a repeated-measure Multivariate ANOVA (MANOVA) of ten dependent variables (the joint QoMs) with the postural condition ([N] vs [SCH]) as a factor. This analysis revealed a significant effect of the postural factor ($F(9, 63) = 2.05^{*}, ^{*}p < 0.05$), with a particularly important drop in the fully-constrained condition (around -5 cm) of the joint QoMs composing the instrumental chain (post-hoc pair-wise comparisons with Least Significant Difference).



(a) (b) (c)

FIGURE 7. Relative displacements of the ten Dempster body joints computed for the corpus of eight round/harsh pairs in the three spatial directions: *X* (medio-lateral), *Y* (antero-posterior), and *Z* (vertical). The displacements are represented as the coefficients of the first eigenmovement (ξ_1^i, $i \in [X, Y, Z]$) obtained by PCA and averaged by postural condition on the eight pairs. The significance of differences of joint ξ_1^i between postural conditions [N/SCH] is given by the p-value issued from post-hoc pair-wise comparisons of repeated-measure MANOVAs: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. (a) (*X* coordinate) Vector ξ_1^X. (b) (*Y* coordinate) Vector ξ_1^Y. (c) (*Z* coordinate) Vector ξ_1^Z.

2) RELATIVE JOINT DISPLACEMENTS

A finer analysis of the cellists' motor distribution through the three spatial directions could be obtained by computing the relative joint displacements within the two body segment chains (*ancillary* and *instrumental*). For each bow pulling movement composing the corpus of eight round/harsh pairs, the PCA decomposition (Eq. 4 and Eq. 5) turned out to be low-dimensional, since the first principal component (ξ_1) captured more than 90 % of the total movement variance. A total of 16 PCAs (8 pairs × 2 postures) was thus performed in order to extract the 30-component vector characterizing the first *eigenmovement* ξ_1 of each sequence.

This methodology produced two samples of 8 × 30 values, one for [N] and the other one for [SCH] postural condition. Fig. 7 presents the first eigenmovement vector along the three spatial axes ($\xi_1^i, i \in [X, Y, Z]$), averaged by postural sample on the eight pairs. A repeated-measure MANOVA of 30 dependent variables (the joint $\xi_1^i, i \in [X, Y, Z]$) was then conducted on the eight sound pairs, and revealed an effect of the postural condition ($F(18, 126) = 4.12^{***}$, $^{***}p < 0.001$). Additional pair-wise post-hoc comparisons with Least Significant Difference (LSD) targeted the significance of this effect only for the vertical between-joints displacements (cf Fig. 7 (Z coordinate)).

The main result of these eigenmovement analyses is illustrated in the rightmost part of Fig. 7 (Z coordinate), which reveals significantly lower vertical displacements for the fully-constrained than for the normal postural condition. Hereby, a primary control immobilization would cause harsher notes principally due to a lack of right arm elevation while pulling the bow. This suggests that the *shoulder opening* movement plays an important role with respect to the produced bow velocity. A subtle trend in the forward/backward direction (Fig. 7 (Y coordinate)) can also be observed, suggesting that a natural backward movement of the head and right shoulder might contribute to a better forward projection of the forearm and the bow. In case of primary control immobilization (fully-constrained condition), the shoulder cannot move back and support the upper arm to ensure a sufficient forward unfolding of the instrumental gesture. This suggests a certain role of the *torso rotation* on the bow pulling movement construction required for producing round sounds.

At this stage of the study, we showed that the joint spatial displacements provide valuable information about the changes in coordination potentially responsible for the harshness phenomenon. An investigation of the musicians' joint angular aspects is further needed to establish a solid connection with the bow velocity.

V. EFFECT OF PRIMARY CONTROL IMPAIRMENT ON THE RIGHT ARM JOINT ROTATIONS

In this part, we go a bit further in the coordination study of the cellists' kinematic chains by analyzing their body joint rotations. Actually, even if human posture can be characterized by the spatial position of each member of the body, a commonly used motion technique consists in computing the angles related to the skeleton geometry [69]. By means of the MoCap Toolbox [52], we thus transformed the cartesian coordinates of the markers composing a Dempster model into its body-related anatomical angles. Note that these angles have been computed globally, i.e. without taking into account their three-axis local projections onto coordinate systems linked to the musicians' segments.

From the previous analysis on relative joint displacements (Sec. IV-B2), we firstly focused on two joint angles during a bow-pulling movement: the right shoulder angle which the mobility proved to be an important parameter for the cello playing on the A string [23], or for the global movement execution among harpists [24]; and the torso rotation which elasticity may facilitate the *forward projection* of the cellists' whole right arm [70], as restoring the body balance after bowing movement achievement [43]. The angle corresponding to the primary control between chest, neck and head might also be relevant.

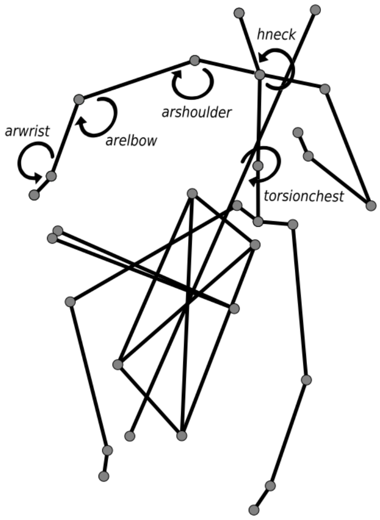


FIGURE 8. Definition of the cellists' five relevant global angles.

In the end, we computed five global angles illustrated in Fig. 8, by a scalar product between two Dempster body segments for each angle (cf Fig. 3(b)):

- **torsionchest** : Torsion angle of the upper chest computed between the segment linking the shoulder markers (*rshoulder/lshoulder*) and the segment linking the hip markers (*rhip/lhip*).
- **hneck** : Neck angle computed between the head segment (*neck/head*) and the chest segment (*midtorso/neck*).
- **ashoulder** : Right shoulder angle computed between the shoulder segment (*neck/rshoulder*) and the upper arm segment (*rshoulder/relbow*).
- **aelbow** : Right elbow angle computed between the upper arm segment (*rshoulder/relbow*) and the forearm segment (*relbow/rwrist*).
- **awrist** : Right wrist angle computed between the forearm segment (*relbow/rwrist*) and the hand segment (*rwrist/rfin*).

A. ANGULAR DESCRIPTORS

1) ANGULAR QUANTITY OF MOVEMENT

As in the case of absolute displacements, the distances travelled by each of the five defined angles were computed as angular Quantities of Movement (QoM), i.e. a sum of all their inter-frame variations:

$$QoMang = \sum_{f=2}^{N} ||\theta_{f-1}^{f}|| \tag{6}$$

where θ_{f-1}^{f} is the angular variation of two body segments between the frames $f-1$ and f, and N is the number of frames corresponding to the duration of the E3 note.

2) ANGULAR LOCATIONS

An angle can present the same quantities of movement for different segment locations between opposite postural conditions. To take into account this information, we computed an angular location for each of the five defined angles, as an average of their values over time:

$$LoCang = \frac{1}{N} \sum_{f=1}^{N} \theta_f \tag{7}$$

where θ_f is an angular value of two body segments at frame f, and N is the number of frames corresponding to the duration of the E3 note.

B. RESULTS

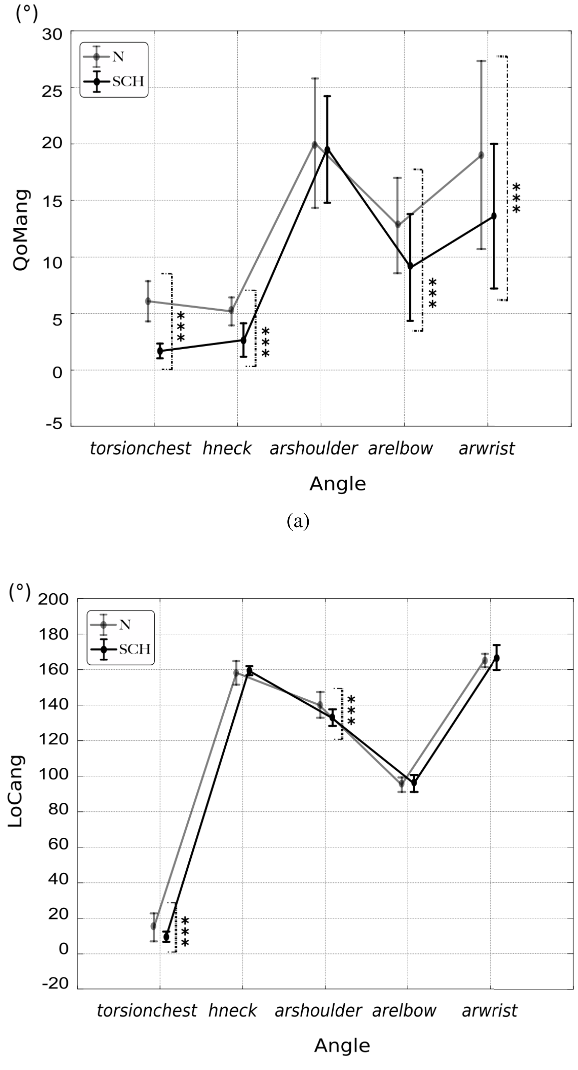
The angular descriptors QoMang (Eq. 6) and LoCang (Eq. 7) have been computed for the five angles on the corpus of eight round/harsh pairs. For each descriptor, this produced two samples of 8×5 values, one for each postural condition [N/SCH]. The Fig. 9 illustrates the average value of the two descriptors for each angle by postural condition.

We performed a repeated-measure MANOVA of ten dependent variables (2 descriptors ×5 angles) with the postural condition as a factor. This analysis revealed a significant effect of the postural factor for each angle ($F(4, 28) = 3.84^*$, $^*p < 0.05$). By means of post-hoc pair-wise comparisons with Least Significant Difference (LSD), we highlighted two main descriptor trends between postural conditions:

- *QoMang descriptor* (cf Fig. 9(a)) : A lower global quantity of movement in condition [SCH] for all angles except for the right shoulder angle.
- *LoCang descriptor* (cf Fig. 9(b)) : A lower mean location (around $-10°$) in condition [SCH] for the torsion chest and right shoulder angles.

C. DISCUSSION

First, the results obtained about mean angular locations (cf Fig. 9(b)) highlight the importance of chest and right shoulder orientations during a natural bow-pulling movement on the A string. Actually, the drop of the *LoCang*



(a)

(b)

FIGURE 9. The locations and quantities of movement descriptors for the five angles averaged on the corpus of eight round/harsh pairs. The significance of differences of *LoCang* and *QoMang* between postural conditions [N/SCH] is given by the p-value issued from post-hoc pair-wise comparisons of repeated-measure MANOVAs: ***$p < 0.001$. (a) Descriptor *QoMang*. (b) Descriptor *LoCang*.

descriptor observed only for these two angles within the fully-constrained postural condition suggests some postural adjustments preliminarily required: The natural twist of the cellists' spine to the left (around 15° in average) may allow them to lean on their left ischium for better preparing the body imbalance caused by the right arm expansion. The prior right shoulder opening which is 10° greater in the normal condition would also contribute to this anticipatory postural strategy: it may allow to better wrap the bowing arm over the A string to accurately reach the E3 note and avoid to make it harsh while pulling the bow. By contrast, the fully-constrained condition would cause a globally narrower right shoulder angle during the pulling movement, since the cellists have to grapple with a lack of muscular strength in their upper back, likely to destabilize the scapular girdle. This *loose shoulder* effect turns out to be compliant with the drop of relative right arm joints displacements observed along the vertical direction (cf Fig. 7(c)).

Second, the results obtained from mean angular quantities of movement (cf Fig. 9(a)) in the fully-constrained situation can be seen as consequences of this lack of anticipatory postural adjustments: Without preliminary spine torsion, the cellists' natural chest rotation (around 6° in average) is limited. The destabilization of the scapular girdle caused by the harness and minerva also halves the natural neck mobility (around 5° in average) linked to primary control. If these postural impairments logically affect the angular displacements of the right elbow and wrist in the motor chain (drop of *QoMang* around $-5°$ in average), it however appears surprising that the angular quantities of movement of the right shoulder globally remain the same between the two opposite conditions (around 20° in average, cf Fig. 9(a)). This result suggests that the shoulder articulation moved in a different way to adapt itself to the postural constraints and somehow ensures the necessary bowing movement.

Finer elements composing this adaptation process can be inferred from the relative joint displacements observed along the antero-posterior direction (cf Fig. 7(b)): the quantities of movement of the right elbow actually turned out to be similar in spite of the limitation in the backwards displacements of the shoulder. Biomechanically, this may suggest that impairments in arm elevation (visible on Fig. 7(c)) and forward projection (visible on Fig. 7(b)), are compensated by an excessive rotation of the forearm on the elbow, turning it outwards the trunk and more backwards than normally. Without postural adjustments, the natural functioning of cellists' shoulder opening during the bow pulling movement would thus be altered, as well as the motor command from the upper arm ensuring the development of an optimal timbre quality [4], [43], [70].

VI. PREDICTION MODEL OF BOW VELOCITIES

In a last step, we attempt to "close the loop" by establishing a connection between the drop in bow velocity measured for the harsh sounds and some key corporeal variables likely to explain it.

A. METHOD

The quantities of movement computed for the five studied angles (*torsionchest, hneck, arshoulder, arelbow, arwrist*) allow to characterize the cellists' global coordination with a small number of parameters. As a consequence, we used them as potential predictors of the bow velocities measured within the corpus of eight round/harsh pairs.

By means of a multiple linear regression method relying on least squares fitting, we built a simple prediction model of bow velocities based on these angular displacements. The technique consisted in searching the fitting coefficients β_i to minimize the mean square difference ϵ^2 between the observed bow velocity values *bowvel* and the values predicted by the model $\widehat{bowvel}$ as linear combinations of angular predictors θ^i, $i \in [1, 5]$:

$$bowvel = \widehat{bowvel} + \epsilon = \sum_{i=1}^{5} \beta_i \theta^i + \epsilon \qquad (8)$$

The vector *bowvel* of observed bow velocities contained 16 values (one for each element of the eight pairs). In the same way, the five independent variables of QoMang predictors θ^i were stored in a table of 16 × 5 values.

TABLE 2. Coefficients β_i of the multiple linear regression model predicting the bow velocities from five angular quantities of movement θ_i on the corpus of eight round/harsh pairs. When significant, the p-value p is affected to each angular predictor by: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

θ_i	torsionchest	hneck	arshoulder	arelbow	arwrist
β_i	2.66*	−1.11	2.32*	1.09	1.62

B. RESULTS

The regression process generated the coefficients β_i (Eq. 8) presented in Tab. 2. These coefficients weight the importance of each associated angular predictor θ^i in the explication of bow velocities. Two angular movement quantities among the five angular predictors turned out to be particularly relevant to model the observed bow velocities: *torsionchest* ($^*p < 0.05$) and *arshoulder* ($^*p < 0.05$). A predictive model of the bow velocities could hereby be inferred from a simple combination of these two displacements:

$$bowvel = 2.66 \times torsionchest + 2.32 \times arshoulder \qquad (9)$$

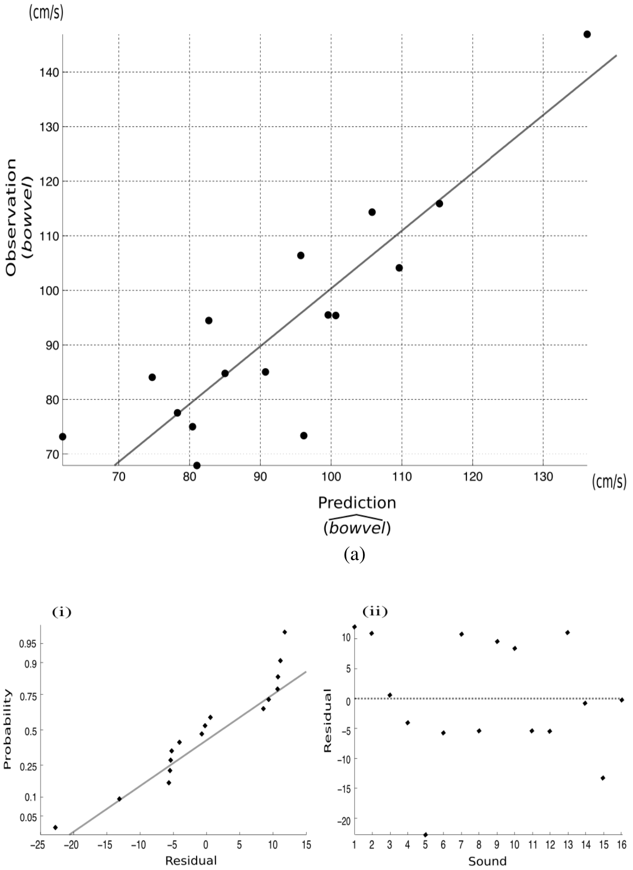
The robustness of this model was checked in several ways: First, the model adapted well to the measured bow velocities ($R^2 = 0.768$, $R^2_{adjusted} = 0.652$, cf Fig. 10(a)). Second, the distribution of regression residuals ϵ validated the assumptions of linearity (Fig. 10(b.i)) and homoscedasticity (Fig. 10(b.ii)).

C. DISCUSSION

The regression model (Eq. 9) reveals that the bow velocities during a bow pulling movement on the A string can be linked to two key corporeal angles, i.e. the right shoulder opening and the torso rotation. Interestingly, these results highlight the same angles as in angular locations analyses (cf Fig. 9(b)). This suggests a fundamental role of the muscular synergy linking the chest to the right shoulder when building optimal bow velocities likely to prevent the production of harsh notes.

As shown by the coefficients of the regression model (Eq. 9), the contribution of each key angle to the bow velocities turns out to be similar. We believe it characterizes a *dynamic balance* that the cellists must conserve between these two key angles during the movement. Referring again to angular location analysis, the accuracy of this motion balance may itself be conditioned by an adequate *static balance* between the same body variables as part of the cellists' whole postural synergy.

Embodiment of these postural balance mechanisms into the bowing technique of highly skilled cellists constitute probative evidence of a *quadrilateral energy transfer* [7]. This fundamental energy transfer actually consists in bringing the energy from the ground by the legs and distribute it to the upper limbs through the spine. Postural constraints may have altered the quadrilateral transfer in at least two different ways: through the harness which prevents the torso rotation by "cutting" the cellists' body into lower and upper parts; and through the minerva which hinders the right shoulder opening by destabilizing the scapular girdle. These constraints also induce a global primary control deficiency, since the neck naturally ensures a central coordinative role between torso rotation and right shoulder opening. In terms of energy, our model links these two variables of the quadrilateral transfer with the physical velocity transmitted to the bow : an insufficient bow velocity responsible for harshness perception (Sec. III) may essentially be caused by a loss of torso rotation or shoulder opening. The contact point of the bow on the A string can thus be considered as a *gravity center* of these energies on the instrument, likely to induce harsh sounds when the postural equilibrium is not respected.



(a)

(b)

FIGURE 10. Multiple linear regression model applied on the corpus of eight round/harsh pairs ($R^2 = 0.768$, $n = 16$). (a) Observed vs. predicted scores of bow velocities. (b.i) Normal probability plot of residuals. (b.ii) Raw dispersion of residuals. (a) Linear regression. (b) Residuals.

VII. CONCLUSION

In this paper, we attempted to trace the postural origins of harsh sounds often produced by highly-skilled cellists in situation of primary control impairment. This process was carried out by comparing specific body joint displacements and rotations issued from a bow pulling gesture on one note of the A string, between a normal playing situation and a constrained one limiting the (ancillary) chest and head movements. In agreement with the bowed-string literature, we revealed that consistent drops in the bow velocity were associated to the signal features of harsh sounds. Analysis of the quantities of joint movement highlighted tighter bowing gestures in the constrained postural situation, characterized by global decreases of the right arm elevation and forward projection to a lesser extent. Through the mean location and displacement analyses of relevant body angles, we also assessed that a primary control impairment may cause an alteration of the synergy which governs the right shoulder opening during a bow pulling gesture. As a consequence, the upper arm might loose its natural bow driving leadership, and cause harsh sounds through an over-sollicitation of the forearm. Finally, a simplified model of the cellists' kinematic chain could be inferred from these angle analyses by relating the bow velocity changes to a postural balance between the right shoulder opening and the upper torso rotation.

Hereby, this study highlights that cello sounds perceived as harsh are not only the result of pure bowing accidents, but also of a lack of *postural flexibility* which affects the bow velocity. This suggests that the motor command of the right arm is piloted by fine sensorimotor mechanisms integrated and *embodied* within the primary control as part of a body language. Main syntactic structures of such a postural language may be implemented through modern environments of virtual reality (AR/VR), in order to propose a tool easing the learning process and enhancing musical expressivity. Such an application would require subsequent investigations targeted on other notes than the one selected here, in order to confirm a general effect of the torso/shoulder coupling on the timbre quality. It might be achieved through the set-up of one or several short experiments involving these notes in a similar context of technical difficulty.

Further investigations should also assess the influence of these postural mechanisms on the bow pressure, which is an other fundamental parameter likely to influence the perceived sound quality. Muscular activity measurements by electromyography (EMG) may also be helpful to confirm that the cellists' forearm plays an excessive role when the primary control is limited. Finally, even if our predictive model reveals interesting information on the influence of a quadrilateral energy transfer linked to the bow velocity variations, it remains simple compared to the numerous degrees of joint freedom composing the human body. A finer decomposition of the cellists' joint angles into triple-axis rotations would therefore be a useful means to better characterize the coordination processes involved in the kinematic chain, as well as compensation effects produced when deprived of their postural adjustments.

REFERENCES

[1] F. Delalande, "La gestique de Gould: éléments pour une sémiologie du geste musical," in *Glenn Gould Pluriel*. Montreal, QC, Canada: Louise Courteau, 1988, pp. 85–111.

[2] C. Cadoz and M. M. Wanderley, *Gesture-Music: Trends in Gestural Control of Music*, vol. 12. Paris, France: Centre Georges Pompidou, 2000.

[3] I. Galamian, G. Mannoni, and E. A. Green, *Enseignement et Technique du Violon*. Paris, France: Van de Velde, 1993.

[4] J. Starker, *An Organized Method of String Playing*. Bloomington, IN, USA: Indiana Univ. Press, 1975.

[5] M. M. Wanderley, "Quantitative analysis of non-obvious performer gestures," in *Gesture and Sign Language in Human-Computer Interaction*. Berlin, Germany: Springer-Verlag, 2002, pp. 241–253.

[6] F. M. Alexander, *The Resurrection of the Body: The Essential Writings of F. Matthias Alexander*. New York, NY, USA: Dell, 1974.

[7] P. De Alcantara, *Technique Alexander Pour Les Musiciens*. Montauban, France: Alexitère, 2000.

[8] J. Rozé, M. Aramaki, R. Kronland-Martinet, and S. Ystad, "Exploring the perceived harshness of cello sounds by morphing and synthesis techniques," *J. Acoust. Soc. Amer.*, vol. 141, no. 3, pp. 2121–2136, 2017.

[9] P. Depalle, R. Kronland-Martinet, and B. Torrésani, "Time-frequency multipliers for sound synthesis," *Proc. SPIE*, vol. 6701, p. 670118, Sep. 2006.

[10] A. Olivero, B. Torrésani, and R. Kronland-Martinet, "A new method for Gabor multipliers estimation: Application to sound morphing," in *Proc. Eur. Signal Process. Conf. (EUSIPCO)*, Aalborg, Denmark, 2010, pp. 507–511.

[11] M. Aramaki, M. Besson, R. Kronland-Martinet, and S. Ystad, "Controlling the perceived material in an impact sound synthesizer," *IEEE Trans. Audio, Speech, Language Process.*, vol. 19, no. 2, pp. 301–314, Feb. 2011.

[12] S. Conan *et al.*, "An intuitive synthesizer of continuous-interaction sounds: Rubbing, scratching, and rolling," *Comput. Music J.*, vol. 38, no. 4, pp. 24–37, Dec. 2014.

[13] S. Conan, O. Derrien, M. Aramaki, S. Ystad, and R. Kronland-Martinet, "A synthesis model with intuitive control capabilities for rolling sounds," *IEEE/ACM Trans. Audio, Speech, Language Process.*, vol. 22, no. 8, pp. 1260–1273, Aug. 2014.

[14] S. Canazza, G. D. Poli, C. Drioli, A. Roda, and A. Vidolin, "Modeling and control of expressiveness in music performance," *Proc. IEEE*, vol. 92, no. 4, pp. 686–701, Apr. 2004.

[15] C. Traube and J. O. Smith, "Extracting the fingering and the plucking points on a guitar string from a recording," in *Proc. IEEE Workshop Appl. Signal Process. Audio Acoust.*, Oct. 2001, pp. 7–10.

[16] M. M. Wanderley and P. Depalle, "Gestural control of sound synthesis," *Proc. IEEE*, vol. 92, no. 4, pp. 632–644, Apr. 2004.

[17] A. P. Carrillo, J. Bonada, E. Maestre, E. Guaus, and M. Blaauw, "Performance control driven violin timbre model based on neural networks," *IEEE Trans. Audio, Speech, Language Process.*, vol. 20, no. 3, pp. 1007–1021, Mar. 2012.

[18] E. Maestre, P. Papiotis, M. Marchini, Q. Llimona, and O. Mayor, "Online access and visualization of enriched multimodal representations of music performance recordings: The quartet dataset and the repovizz system," *IEEE Multimedia Mag.*, vol. 24, no. 1, pp. 24–34, Jan. 2017.

[19] A. Gritten and E. King, *New Perspectives on Music and Gesture*. Farnham, U.K.: Ashgate, 2011.

[20] M. Leman, "Musical gestures and embodied cognition," in *Proc. J. Inform. Musicale*, 2012, pp. 5–7.

[21] M. M. Wanderley, B. W. Vines, N. Middleton, C. McKay, and W. Hatch, "The musical significance of clarinetists' ancillary gestures: An exploration of the field," *J. New Music Res.*, vol. 34, no. 1, pp. 97–113, 2005.

[22] F. Bejjani and N. Halpern, "Postural kinematics of trumpet playing," *J. Biomech.*, vol. 22, no. 5, pp. 439–446, 1989.

[23] L. Turner-Stokes and K. Reid, "Three-dimensional motion analysis of upper limb movement in the bowing arm of string-playing musicians," *Clin. Biomech.*, vol. 14, no. 6, pp. 426–433, 1999.

[24] D. Chadefaux, J.-L. Le Carrou, M. M. Wanderley, B. Fabre, and L. Daudet, "Gestural strategies in the harp performance," *Acta Acustica*, vol. 99, no. 6, pp. 986–996, 2013.

[25] A. R. Jensenius, "Action-sound: Developing methods and tools to study music-related body movement," Ph.D. dissertation, Dept. Musicol., Univ. Oslo, Oslo, Norway, 2007.

[26] M. R. Thompson and G. Luck, "Exploring relationships between pianists' body movements, their expressive intentions, and structural elements of the music," *Musicae Sci.*, vol. 16, no. 1, pp. 19–40, 2012.

[27] C. Palmer, E. Koopmans, J. D. Loehr, and C. Carter, "Movement-related feedback and temporal accuracy in clarinet performance," *Music Perception, Interdiscipl. J.*, vol. 26, no. 5, pp. 439–449, 2009.

[28] S. Dahl, "The playing of an accent–preliminary observations from temporal and kinematic analysis of percussionists," *J. New Music Res.*, vol. 29, no. 3, pp. 225–233, 2000.

[29] C. Drake and C. Palmer, "Skill acquisition in music performance: Relations between planning and temporal control," *Cognition*, vol. 74, no. 1, pp. 1–32, 2000.

[30] M. Wiesendanger, A. Baader, and O. Kazennikov, "Fingering and bowing in violinists: A motor control approach," in *Music, Motor Control and the Brain*. Oxford, U.K.: Oxford Univ. Press, 2006, pp. 109–123.

[31] R. I. Godøy, "Understanding coarticulation in musical experience," in *Proc. Int. Symp. Comput. Music Multidiscipl. Retr.*, 2013, pp. 535–547.

[32] J. W. Davidson, "Qualitative insights into the use of expressive body movement in solo piano performance: A case study approach," *Psychol. Music*, vol. 35, no. 3, pp. 381–401, 2007.

[33] C. Palmer, E. Koopmans, C. Carter, J. D. Loehr, and M. M. Wanderley, "Synchronization of motion and timing in clarinet performance," in *Proc. Int. Symp. Perform. Sci.*, 2009, pp. 1–6.

[34] H. Winold and E. Thelen, "Coordination and control in the bow arm movements of highly skilled cellists," *Ecol. Psychol.*, vol. 6, no. 1, pp. 1–31, 1994.

[35] G. Shan and P. Visentin, "A quantitative three-dimensional analysis of arm kinematics in violin performance," *Med. Problems Performing Artists*, vol. 18, no. 1, pp. 3–10, 2003.

[36] F. Visi, E. Coorevits, E. Miranda, and M. Leman, "Effects of different bow stroke styles on body movements of a viola player: An exploratory study," in *Music Technology Meets Philosophy: From Digital Echos to Virtual Ethos*. Ann Arbor, MI, USA: Univ. of Michigan, 2014.

[37] P.-J. Maes, M. M. Wanderley, and C. Palmer, "The role of working memory in the temporal control of discrete and continuous movements," *Exp. Brain Res.*, vol. 233, no. 1, pp. 263–273, 2015.

[38] J. Rozé *et al.*, "Assessing the influence of constraints on cellists' postural displacements and musical expressivity," in *Music, Mind, and Embodiment* (Lecture Notes in Computer Science), vol. 9617. Cham, Switzerland: Springer, 2016, pp. 22–41.

[39] M. L. Knapp, J. A. Hall, and T. G. Horgan, *Nonverbal Communication in Human Interaction*. Boston, MA, USA: Cengage Learning, 2013.

[40] M. M. Wanderley, "Non-obvious performer gestures in instrumental music," in *Proc. Int. Gesture Workshop*, 1999, pp. 37–48.

[41] L. Goossens and E. Roxburgh, *Oboe*. New York, NY, USA: Schirmer, 1977.

[42] D. Hoppenot, *Le Violon Intérieur*. Paris, France: Van de Velde, 1981.

[43] G. Mantel, *CELLO TECHNIQUE: Principles and Forms of Movement*. Bloomington, IN, USA: Indiana Univ. Press, 1995.

[44] R. S. Hatten, *Interpreting Musical Gestures, Topics, and Tropes: Mozart, Beethoven, Schubert*. Bloomington, IN, USA: Indiana Univ. Press, 2004.

[45] T. E. Prieto, J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust, "Measures of postural steadiness: Differences between healthy young and elderly adults," *IEEE Trans. Biomed. Eng.*, vol. 43, no. 9, pp. 956–966, Sep. 1996.

[46] K. Guettler, E. Schoonderwaldt, and A. Askenfelt, "Bow speed or bowing position—Which one influences spectrum the most?" in *Proc. Stockholm Music Acoust. Conf.*, 2003, pp. 1–4.

[47] F. Desmet, L. Nijs, M. Demey, M. Lesaffre, J.-P. Martens, and M. Leman, "Assessing a clarinet player's performer gestures in relation to locally intended musical targets," *J. New Music Res.*, vol. 41, no. 1, pp. 31–48, 2012.

[48] O. Lartillot and P. Toiviainen, "A MATLAB toolbox for musical feature extraction from audio," in *Proc. Int. Conf. Digit. Audio Effects*, Sep. 2007, pp. 237–244.

[49] R. McAulay and T. Quatieri, "Speech analysis/synthesis based on a sinusoidal representation," *IEEE Trans. Acoust., Speech, Signal Process.*, vol. ASSP-34, no. 4, pp. 744–754, Aug. 1986.

[50] T. Tolonen and M. Karjalainen, "A computationally efficient multipitch analysis model," *IEEE Trans. Speech Audio Process.*, vol. 8, no. 6, pp. 708–716, Nov. 2000.

[51] W. T. Dempster, "Space requirements of the seated operator, geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs," Dept. Aero Med. Lab., Univ. Michigan, Ann Arbor, MI, USA, Tech. Rep. 55-159, Jul. 1955.

[52] B. Burger and P. Toiviainen, "MoCap toolbox—A MATLAB toolbox for computational analysis of movement data," in *Proc. Sound Music Comput. Conf.*, 2013, pp. 1–8.

[53] J. M. Grey and J. W. Gordon, "Perceptual effects of spectral modifications on musical timbres," *J. Acoust. Soc. Amer.*, vol. 63, no. 5, pp. 1493–1500, 1978.

[54] C. Fritz, A. F. Blackwell, I. Cross, J. Woodhouse, and B. C. J. Moore, "Exploring violin sound quality: Investigating English timbre descriptors and correlating resynthesized acoustical modifications with perceptual properties," *J. Acoust. Soc. Amer.*, vol. 131, no. 1, pp. 783–794, 2012.

[55] A. Askenfelt, "Measurement of the bowing parameters in violin playing," *The J. Acoust. Soc. Amer.*, vol. 29, no. 1, pp. 1–30, 1988.

[56] J. C. Schelleng, "The bowed string and the player," *J. Acoust. Soc. Amer.*, vol. 53, no. 1, pp. 26–41, 1973.

[57] K. Guettler, "Looking at starting transients and tone coloring of the bowed string," in *Proc. Frontiers Res. Speech Music*, 2004, pp. 1–10.

[58] J. Rozá, M. Aramaki, R. Kronland-Martinet, C. Bourdin, and S. Ystad, "Eluding the influence of postural constraints on cellists' bowing movements and timbral quality," in *Bridging People and Sound* (Lecture Notes in Computer Science), vol. 10525. Heidelberg, Germany: Springer-Verlag, 2017, pp. 128–144.

[59] A. Savitzky and M. J. E. Golay, "Smoothing and differentiation of data by simplified least squares procedures," *Anal. Chem.*, vol. 36, no. 8, pp. 1627–1639, 1964.

[60] S. B. Davis and P. Mermelstein, "Comparison of parametric representations for monosyllabic word recognition in continuously spoken sentences," *IEEE Trans. Acoust., Speech, Signal Process.*, vol. ASSP-28, no. 4, pp. 357–366, Sep. 1980.

[61] G. Peeters, "A large set of audio features for sound description (similarity and classification) in the cuidado project," IRCAM, Paris, France, Tech. Rep. Version 1.0, 2004.

[62] M. Chudy, A. P. Carrillo, and S. Dixon, "On the relation between gesture, tone production and perception in classical cello performance," in *Proc. Meetings Acoust.*, vol. 19, 2013, p. 035017.

[63] N. A. Bernstein, *The Co-Ordination and Regulation of Movements*. New York, NY, USA: Pergamon, 1935.

[64] M. T. Turvey, "Coordination," *Amer. Psychol.*, vol. 45, no. 8, p. 938, 1990.

[65] B. Burger, M. R. Thompson, G. Luck, S. Saarikallio, and P. Toiviainen, "Influences of rhythm- and timbre-related musical features on characteristics of music-induced movement," *Frontiers Psychol.*, vol. 4, p. 183, Apr. 2013.

[66] P. Toiviainen, G. Luck, and M. R. Thompson, "Embodied meter: Hierarchical eigenmodes in music-induced movement," *Music Perception, Interdiscipl. J.*, vol. 28, no. 1, pp. 59–70, 2010.

[67] D. Amelynck, P.-J. Maes, J. P. Martens, and M. Leman, "Expressive body movement responses to music are coherent, consistent, and low dimensional," *IEEE Trans. Cybern.*, vol. 44, no. 12, pp. 2288–2301, Dec. 2014.

[68] L. Naveda, I. C. Martinez, J. Dameśon, A. Ghiena, R. Herrera, and A. Ordás, "Methods for the analysis of rhythmic and metrical responses to music in free movement trajectories," in *Proc. 11th Int. Symp. Comput. Music Multidiscipl. Res. (CMMR)*, 2015, pp. 248–262.

[69] J. Droulez and A. Berthoz, "Servo-controlled (conservative) versus topological (projective) mode of sensory motor control," in *Disorders of Posture and Gait*. Amsterdam, The Netherlands: Elsevier, 1986.

[70] X. Gagnepain, *Du Musicien en Général, au Violoncelliste en Particulier*. Paris, France: Cité de la Musique, 2001.

JOCELYN ROZÉ received the master's degree in software engineering in 2003 and the Ph.D. degree in acoustics from Aix-Marseille University in 2017. Having a passion for the cello, his research interests explore the fine sound/gesture relationships between the cellists and their instrument. He is particularly interested in the role of postural sensations (or statesthesy) during the elaboration of musical expressivity. He believes that musicians' health and instrumental pedagogy can benefit from a better understanding of human primary postural directions.

MITSUKO ARAMAKI received the Ph.D. degree from Aix-Marseille University, Marseille, France, in 2003, with a focus on the analysis and synthesis of impact sounds using physical and perceptual approaches. She was with the Institut de Neurosciences Cognitives de la Méditerranée, Marseille, from 2006 to 2011. From 2012 to 2016, she joined the Laboratoire de Mécanique et d'Acoustique, Marseille. Since 2017, she has been the Head of the Perception Engineering Team, PRISM (Perception, Representations, Image, Sound, Music) Laboratory, where she is currently a Researcher with the National Center for Scientific Research. She has published 30 articles in international peer-reviewed journals, over 40 articles in international conference proceedings, and co-edited seven books published by Springer in their series LNCS. Her research mainly focused on sound modeling, perceptual and cognitive aspects of timbre, neuroscience methods, and multimodal interactions in the context of virtual/augmented reality. She is a member of the Computer Music Multidisciplinary Research Steering Committee and is regularly involved in the chair panel of the conference.

RICHARD KRONLAND-MARTINET received the master's degree in theoretical physics, the Ph.D. degree in acoustics, and the Doctorat d'Etat ès Sciences degree (habilitation) for his pioneer work on the analysis and synthesis of sounds using time–frequency and time-scale (wavelets) representations from Aix-Marseille University, France, in 1980, 1983, and1989, respectively. He is currently the Director of Research with the National Center for Scientific Research and the Head of the Interdisciplinary PRISM (Perception, Representations, Image, Sound, Music) Laboratory. He published over 250 journal articles and conference proceedings in this domain. He recently addressed new scientific challenges linked to the semantic description of sounds and to their synthesis control using an interdisciplinary approach associating signal processing, physics, perception and cognition, and based on sound invariants. His primary research interests are in the analysis and synthesis of sounds with a particular emphasis on high-level control of synthesis processes.

SØLVI YSTAD received the degree in civil engineering in electronics from Norges Tekniske Høgskole, Trondheim, Norway, in 1992, and the Ph.D. degree in acoustics from the University of Aix-Marseille II, France, in 1998. After a postdoctoral year at Stanford University, she received a permanent research position at the National French Research Center. Since 2017, she has been with the PRISM (Perception, Representations, Image, Sound, Music) Laboratory, Marseilles. Her research activities mainly focus on sound modeling and in particular the identification of perceptually relevant sound structures that enable the elaboration of new interfaces and synthesis devices for intuitive control of sounds.

• • •