Assessing the influence of constraints on cellists' postural displacements and musical expressivity

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Abstract. This article presents the preliminary results from an experiment investigating the influence of cellists' ancillary gestures on their musical expressivity. Seven professional cellists were asked to play a score while their movements were recorded by a force platform (on which they were seated) and a 3D motion capture system for joint kinematics. Specific torso and head contributions to their global postural displacements were analyzed through the use of 4 playing conditions: (a) one *normal* condition without any constraints, (b) one *mentally static* condition where the cellists were asked to keep their posture as static as possible, (c) one *physically semi-constrained* condition where the cellists' torso was attached to the back of a chair by a safety race harness, and (d) one *physically fully constrained* condition where the cellists wore a neck collar in addition to the race harness to limit their head movements. We here investigate the influence of these constraints on global postural features computed from the force platform data, and on fundamental acoustical features linked to musical expressivity for one cellist. The first results reveal that the cellists' immobilization conditions give rise to different postural adaptation strategies depending on the torso-head coupling, and alter significantly the expressive intentions through changes in rhythm, dynamics and timbre of the produced sounds.

Keywords: Cellist, music, ancillary/postural gestures, force platform, acoustical features, performance

1 Introduction

1.1 Background

The expressive play of a musician is intrinsically connected to his or her gestures. These connections have been thoroughly investigated through the embodied music cognition approach (Leman 2007). While continuously interacting with the instrument, the player's body encodes sensorymotor information that induces a spontaneous reenaction of musical gestures from the perceived audio. This information determines the player's motor process as a function of the instrument's ergonomy, the musical structure and interpretative choices (Wanderley 2002). Some studies directly investigated connections from score structure to interpretation through a note by note analysis (De Poli et al. 1998, Barthet et al. 2007). Others explored the musician's body as a mediator of expressive sensitivities according to two gestural levels (Cadoz and Wanderley 2000): The effective or instrumental gestures, which are directly at the origin of the produced sound, and the ancillary or accompanist gestures, that are not directly responsible for the sound production, but that might ease the performer-instrument interaction. The musical significance of such ancillary gestures has been investigated in the case of the clarinet (Wanderley 2005, Desmet et al. 2012), the piano (Thompson and Luck 2011), the harp (Chadefaux et al. 2013), and the violin (Visi et al. 2014). Results from these studies showed that ancillary movements play an important role in the musicians' expressive intentions, by supporting the phrasing, and facilitating technical gestures. The previous findings also highlighted that the influence of ancillary gestures on a given expressive audio feature varies according to the instrument.

1.2 Motivation

In line with previous research, we're interested in better understanding the significance of ancillary gestures for professional cellists, in particular their postural displacements, in relation with the musical expressivity. Some studies examined the influence of physical parameters of the cello bow on spectral features (Askenfelt and Guettler 2001, Chudy et al. 2013). Others extracted coordination patterns of joint movements in the cellists' bowing arm to characterize musicality (Winold et al. 1994), or attempted to identify trends of cellists' motor process through expressive timing and dynamic audio features (Hong 2003). However, to our knowledge, no studies have so far investigated in depth the relationship between cellists' postural displacements and their musical expressivity. An insight in this exciting field can be obtained from experimental concepts described in *The Alexander technique* adapted to the cello (De Alcantara). In fact, F.M. Alexander demonstrated that a specific orientation of the cellists' head, neck, and upper back enables optimal body coordination. What would happen to the produced sound if we perturb this perfect body coordination described by Alexander? To find some answers to this question, we decided to constrain the cellists' natural postural adjustments and observe the effects on expressivity.

2 Aims and hypothesis

This paper presents preliminary results of a large experiment aiming at investigating the influence of professional cellists' postural displacements on their musical expressivity. A multi-modal environment combining a force platform, motion-capture, and audio recordings was used. Cellists were asked to play a score as expressively as possible in 4 types of postural conditions, and according to *legato* or *detached* playing modes with two different tempi *(slow/fast)*. We here explore the influence of such immobilization conditions on a global postural measure and on acoustic descriptors relevant for musical expressivity. Moreover, results described in this paper will only focus on variations depending on the playing mode and not on the tempo. We predicted that modifications induced by immobilization constraints on the cellist's postural coordination, and particularly the torso-head connection, will be explicitly revealed by the selected postural and acoustical descriptors, with substantial differences according to the playing mode.

3 Experiment

3.1 Participants

Seven professional cellists (4 males, 3 females) were invited to participate in the experiment. All the participants had received professional music training, some of them hold a position at the Opera of Marseille and all are renown cello teachers. They all gave written consent and were payed for the participation. In this paper, we mainly focus on one of the female cellists.

3.2 Scores

Design. The choice of an adequate score as support of investigation for ancillary gestures, requires some thoughts. Selections from the standard cello repertoire are colored by emotional connotations, which can result in very different natural bowing and fingerings strategies, according to the chosen interpretation. This is a problem with respect to our objectives. Actually we're looking for adaptive postural strategies, as function of the musical structure, and not of a particular expressive intent. This implies the use of a sufficiently annotated score material, adaptable to different bow strokes and tempi, and not too loaded with affective emotional content. Hereby a common base for decoding and comparing cellists' ancillary gestures can be obtained. Consequently, we decided to design a special expressive score, combining short study fragments of cello suite excerpts from the Bach repertoire in which specific bowing strokes and fingering positions are imposed. The score is composed of 6 parts, each related to specific difficulties of cello playing. In this paper we focus on 2 parts that correspond to fast syncope shifts of the left hand *(Part 4)* and cross-string movements of the bowing arm *(Part 5)* (Fig. 1).

Qualitative factors. Our experiment explored cellists' postural displacements according to qualitative factors of playing modes and global tempi. The *detached* playing mode is characterized by the fact that each bow stroke produced a single note, while *legato* mode is obtained when several notes are played by the same stroke. To take into account the playing modes, we designed 2 versions of the same score with different lengths of note ties. We'll focus here on the slow tempo.

Fig. 1. *(Left)* **Part 4** of the score: Fast syncope shifts of the left hand. *(Right)* **Part 5**: Cross-string movements of the bowing arm. For each part, 2 versions of the partition exist : a.*(Top)* ***Detached*** *playing mode*, b.*(Bottom)* ***Legato*** *playing mode*

3.3 Apparatus

The investigation of the cellists' postural strategies in different playing conditions was made possible by several experimental devices.

Force platform. The cellists were seated with their instrument on a force platform AMTI (model SGA34CE), a dynamometrical plate capturing the forces and moments applied on its surface. Collected at a frame rate of 250 Hz, these data allowed us to compute the COP (Center Of Pressure) projection for the system {cellist-instrument} at the interface of the platform. Several useful descriptors could be computed from the trajectories described by the COP, taken as a global postural measure.

Mocap system. To get finer details on postural adjustments and segmental coordination of performers, a 3D tracking motion capture system (VICON) was used. This system consisted in a network of 8 high-speed infrared cameras distributed around the performer, and acquiring kinematic data at a frame rate of 125 Hz. These recordings will not be discussed in this article.

Audio and video recordings. Audio data were recorded at a 44.1 kHz sampling rate via a MOTU interface (Ultralite MIC3) from a microphone DPA 4096 placed under the cello bridge. The full performance was recorded by a standard digital video camera to disambiguate Mocap data when needed. As for the mocap, video recordings won't be discussed here.

3.4 Protocol

Constraints and materials. The experimental procedure was divided in 4 sessions corresponding to 4 different postural playing conditions (Fig. 2):

1. **N :** ***Normal condition***. Cellists were asked to play naturally as in a performance context.

2. **SM : *Static Mental condition***. Cellists were asked to be as immobile as possible while playing.
3. **SC : *Static Chest condition***. Cellists were asked to play in a physically semi-constrained situation, with the torso attached to the back of their chair by a 5-point safety race harness that did not constrain their shoulder movements.
4. **SCH : *Static Chest and Head condition***. Cellists were asked to play in a physically fully constrained situation, with the torso attached as in the SC condition and a neck collar adjusted to limit their head movements.

In all the conditions the cellists were asked to play as expressively as possible. As the material weight varies according to the condition, the force platform was re-calibrated between each postural session.

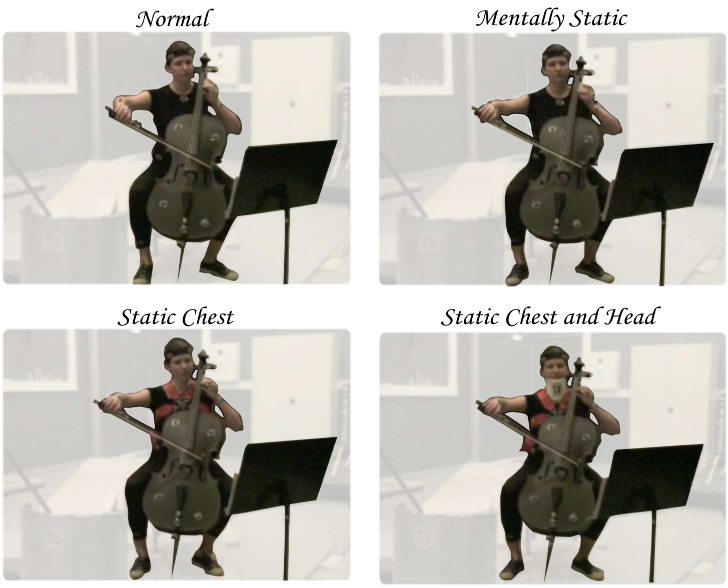

Fig. 2. The 4 postural conditions of experiment : *(TopLeft)* Condition Normal (**N**), *(TopRight)* Condition Static Mental (**SM**), *(BottomLeft)* Condition Static Chest (**SC**), *(BottomRight)* Condition Static Chest and Head (**SCH**)

Design. For each postural session, the experimental design included 2 playing modes (legato/detached) x 2 tempi (slow/fast) x 3 repetitions within-subjects, resulting in 12 takes by session and by subject. The 4 experimental sessions were proceeded in a different order for each cellist, to avoid order effects. In the same way, the order of execution for playing modes, tempi, and repetition modalities within each session were randomized. Hence, the chronological order achievement of the 12 session takes was different for each subject. This design yielded a total of 12 takes x 4 sessions = 48 trials by cellist.

Procedure. The musicians received the score before the day of experiment, to familiarize with bow strokes and fingerings printed in the 2 score versions. Upon arrival, each cellist was informed about the procedure and signed a consent form. The musicians were asked to play as expressively as possible whatever the postural condition. At the beginning of each recording session, the musicians were equipped according to the material required by the postural condition. For each take, the playing mode and tempo was given. A clap was used as mean for synchronizing all the signals collected from the platform, the motion capture, the audio and video devices. Once the clap emitted, an operator indicated the global tempo to the musician through 4 metronome beats. The cellist then started to play on the 5th beat (without the metronome). Each postural session was separated by a short break. At the end of each session, the musicians were invited to answer a short questionnaire. This enabled a better understanding of the potential discomfort experienced during the postural instructions and how the musicians felt that the constraint influenced the movements and the sound. The entire experiment lasted for approximately 4 hours for each cellist.

4 Analysis methods

4.1 Postural analysis

The COP displacements of the system {cellist-instrument} on the force platform stand for its postural oscillations as a function of time. A common method for postural analysis consists in estimating the ellipse encompassing 95% of the COP data points on the trial duration. We estimated 3 relevant descriptors from the geometrical features of this COP confidence ellipse to characterize the global postural behavior of the subject: Area, Principal orientation and Flatness.

1. **Area**. The area of the ellipse is an estimation of the total surface covered by 95% of the COP displacements.
2. **Orientation**. The two main ellipse orientations are computed by a principal component regression on COP centered data. This process results in a pair of orthogonal components standing for the 2 trigonometrical angles of semi-major and semi-minor axes. The first component (the angle of semi-major axis) characterize the main direction of postural displacement.
3. **Flatness**. The flatness of the ellipse was computed from its eccentricity, a measure obtained from the ratio between its semi-major and semi-minor axes, which provide information on how circular the ellipse is. The eccentricity e is given by :

$$e = \sqrt{1 - \frac{b^2}{a^2}} \tag{1}$$

with a, b respectively the semi-major and the semi-minor axes.

- If $e \simeq 0$, the ellipse is quasi-circular
- If $e \simeq 1$, the ellipse approaches a straight line

The combination of the main orientation and eccentricity of the ellipse enabled the antero-posterior *(forward/backward)* or medio-lateral *(left/right)* tendency of postural displacements. The COP descriptors were computed on a full score sequence (Fig. 3).

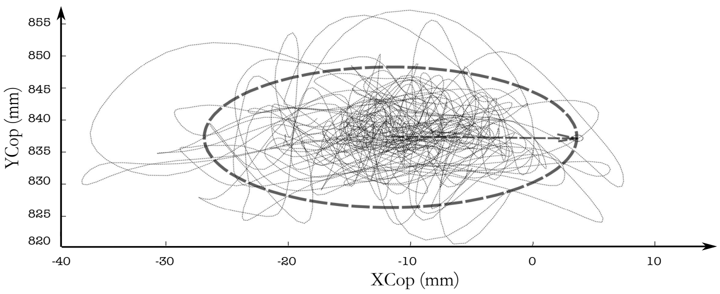

Fig. 3. Exemple of **Confidence ellipse** estimated from COP displacements of the system {cellist-instrument} on the force platform. The sequence is a player's trial in *StaticChest* postural condition

4.2 Audio analysis

A very preliminary step of audio analysis consisted in manually segmenting the session's audio recordings into the 6 score parts, with the help of the Praat software. Then, to produce relevant correlations between the postural/ancillary displacements and their sound attributes, we needed to perform a note-by-note analysis.

Pitch extraction. Given the huge amount of data to process, this step would have been too tedious to process by hand. Consequently, we adapted an audio pitch tracking algorithm from the Matlab MIR toolbox (Lartillot et al. 2007). The method is based on the computation of an autocorrelation function corresponding to periodicities in the spectrum signal frames.

Acoustical descriptors. As a first approach, the musical expressivity was characterized by 3 fundamental audio descriptors related to rhythmic deviations, dynamic and timbre modulations. By dividing the audio signal in frames overlapped by a factor compatible with the frame rate of the mocap system, i.e 8 ms *(1/125Hz)*, an estimation of the continuous evolution of the descriptors with respect to time could be obtained. This step was a prerequisite to allow future investigations between audio and kinematic functional data.

1. **Rhythmic**. To obtain a descriptor related to the rhythmic deviations, the IOIs (Inter-onset interval) between each successive note was calculated from the note attack positions. The IOIs could be assimilated to total note durations, since all the note transitions were continuous. Moreover, as an indirect measure of local tempo variations on each note, IOIs provide a relevant way to get information on the rubato quality of an expressive phrasing. For each note n of the sequence, the rhythmic descriptor was computed as an IOI note deviation from its theoretical duration :
$$Rhythmic(n) = \frac{IOI_t(n)}{IOI_r(n)} \times BPM \tag{2}$$
with $IOI_t(n)$, $IOI_r(n)$ denoting respectively theoretical and real IOIs of the note n, and BPM denoting the theoretical global tempo (i.e. 45 BPM).
2. **Dynamic**. The envelope was calculated by the RMS (Root Mean Square) value of each audio frame composing the sequence (Kim et al. 2005). From here, we could get the mean intensity of each note, simply by averaging the RMS frame values on the note length. For each note n of the sequence, the dynamic descriptor reflected its mean intensity :
$$Dynamic(n) = \frac{1}{l_{n+1} - l_n} \sum_{l=l_n}^{l_{n+1}} \sqrt{\frac{1}{N_w} \sum_{i=1}^{N_w} s_{i,l}^2} \tag{3}$$
with ln, l_{n+1} denoting respectively the attack frame indexes of note n and note $n{+}1$, N_w the window size for the frames of the audio signal s.
3. **Timbre**. The choice of the most adequate timbre descriptors that at best characterize tone color changes between postural conditions is intricate. By attentively listening to the sound recordings, certain differences between postural conditions could be heard, and were perceived as spectral enrichments (gain in *roundness*) or impoverishments (gain in *harshness* and metallic aspect). To reveal these phenomena through timbre descriptors, we firstly computed the standard HSC (Harmonic Spectral Centroid). However, very small changes emerged from this global *Brightness* descriptor. A more detailed investigation was then effectuated in 3 different subbands of the spectrum using the Tristimulus descriptor (Pollard and Jansson 1982). This descriptor led to more relevant results for characterizing the spectral evolutions appearing in the sound material. The tristimulus characterizes the spectral energy distribution by three coordinates TR1, TR2 and TR3, which correspond to spectral barycenter computations in 3 subbands. The tristimulus coordonates are computed for each note n as an average of the amplitude values between the attack frame indexes l_n of note n, and l_{n+1} of note $n{+}1$:

$$TR1(n) = \frac{1}{l_{n+1} - l_n} \sum_{l=l_n}^{l_{n+1}} \frac{A_{1,l}}{\sum_{h=1}^{H} A_{h,l}} \quad : \textit{Relative energy of the fundamental}$$

$$TR2(n) = \frac{1}{l_{n+1} - l_n} \sum_{l=l_n}^{l_{n+1}} \frac{\sum_{h=2}^{4} A_{h,l}}{\sum_{h=1}^{H} A_{h,l}} \quad : \textit{Relative energy of harmonics 2 to 4}$$

$$TR3(n) = \frac{1}{l_{n+1} - l_n} \sum_{l=l_n}^{l_{n+1}} \frac{\sum_{h=5}^{H} A_{h,l}}{\sum_{h=1}^{H} A_{h,l}} \quad : \textit{Relative energy of harmonics 5 to H}$$

with $A_{h,l}$ denoting the spectral amplitude of harmonic of rank h at the frame l. H denotes the total number of harmonics taken into consideration.
The sum of the 3 tristimulus coordonates always equals 1, and thus describes how the energy is distributed in the 3 spectral bands. Hence, we proposed an upper harmonic strength descriptor related to the perceived harshness for each note n, as follows:

$$Harshness(n) = \frac{TR3(n)}{TR1(n) + TR2(n)} \tag{4}$$

- If the *harshness* is low, the note sounds round with more presence.
- If the *harshness* is high, the note sounds harsh, scratchy and more metallic.

5 Results and discussions

We here discuss the influence of the experimental conditions on postural and musical features.

5.1 Influences on the posture

For each postural condition, we computed the geometrical features of a COP confidence ellipse, obtained by averaging the 3 COP ellipses corresponding to each repetition of the same playing mode/tempo combination. The comparisons revealed two different levels of postural influence:

Influence of playing modes Concerning the cellist under examination, the main effect of the playing mode was a global decrease of the ellipse area in ***Normal*** condition from *detached* to *legato* mode. In the static postural conditions, the ellipses' geometrical features remained relatively consistent between the two playing modes (Fig. 4). The same kind of comparison realized across all the cellists, revealed that for a given postural condition, the mean ellipse area of their postural displacements was globally smallest in *legato* than in *detached* playing mode (Fig. 5). Surprisingly, this might indicate, in a rather counter intuitive manner, a global and natural tendency for cellists to reduce the amplitude of their postural oscillations while performing wider bowing movements.

Influence of constraints The postural descriptors revealed some interesting effects of postural conditions on the geometrical features of the ellipse.

For the ***Normal*** condition of the cellist under examination, the major part of her postural displacements appeared to occur in a right-frontal diagonal direction, principally as an anteroposterior component. This forward direction can be well explained by the dynamical resistance opposing musician and instrument, because the cellist naturally uses the force resistance of her instrument to gain in postural stability. Besides, the decreasing amplitude of postural oscillations observed while playing *legato* coincides most likely with a stronger chest immobilization, to ensure a continuous control of arm movements. Therefore, the ellipse's features of normal COP displacements might reflect a natural strategy to decrease the amount of effort carried out by the upper limbs, and especially by the right bowing arm.

For the ***Static Mental*** condition, the cellist's mental immobilization led to a systematic decrease of postural ellipse's areas for the two playing modes (Fig. 4). On the other hand, the global ellipse orientation in this condition remained quite similar to the normal one. Interestingly, this mental constraint therefore revealed that some cellists' habits are so ingrained, that they cannot be completely inhibited. In spite of the cellist's efforts, an incompressible postural quantity of movement always seems to subsist. This seems to be valid for almost all the cellists (Fig. 5), which complies with studies on clarinetists' ancillary gestures (Wanderley 2005).

For the ***Static Chest*** condition, the physical immobilization by torso harnessing led to a reduction of the ellipse area for the cellist investigated, whatever the playing mode (Fig. 4). Moreover, this constraint tended to reduce the ellipse flatness with respect to the normal condition, with a global more rounded shape. It could also be noticed that the ellipse orientation of this condition differs significantly from the others, since the main direction of postural displacement becomes lateral, with an opposite sense between *detached* and *legato* playing modes. Nevertheless, if the chest constraint resulted in small lateral displacements for this particular cellist, we discovered that this was absolutely not a general tendency followed by all the cellists (Fig. 5). Indeed, it was not rare to observe the reverse situation in which the postural displacements were wider for the semi-constrained condition than for the normal one. We suppose that these contrasted reactions might result from the anti-natural character of the constraint. Forcing a cellist to perform with the back stuck to the chair, breaks the dynamical resistance with his instrument. To maintain an optimal expressive way of playing, the musician might react by reorganizing his corporeal synergies and adopting compensation strategies, depending on his morphology and playing techniques.

For the ***Static Chest Head*** condition, the ellipse features surprisingly seemed to realign with the normal case for the cellist investigated (Fig. 4). Ellipse orientation and flatness were indeed very similar to the normal condition. Only the ellipse area was smaller in this constraint with respect to the normal situation for the *detached* playing mode. This result might reveal the importance of the chest-head coupling for the global postural displacements. Regarding this particular cellist, it seems as though the unity between the chest and the head must be ensured with or without constraint, to achieve optimal postural movements.

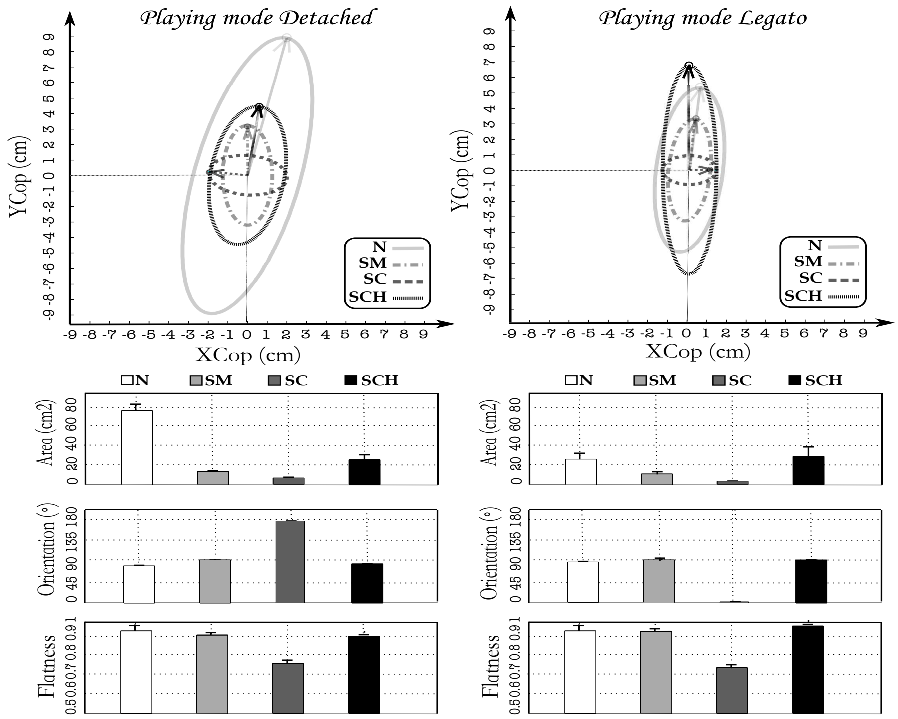

Fig. 4. COP ellipse descriptors averaged on 3 repetitions of a full cellist's sequence, for each postural condition and for each playing mode. **Ellipse geometrical shapes** are drawn in *Detached mode (TopLeft)* and *Legato mode (TopRight)*. Corresponding **COP descriptors** are given in *Detached mode (BottomLeft)* and *Legato mode (BottomRight)*

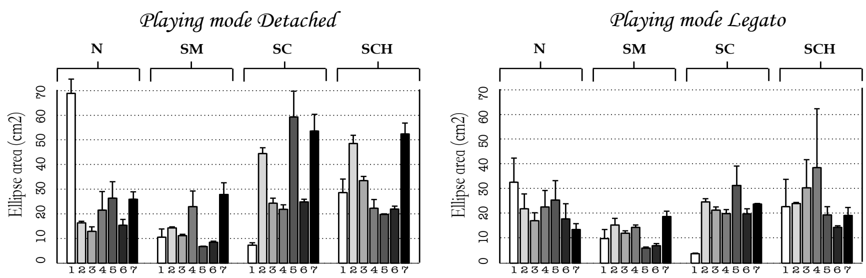

Fig. 5. COP ellipse areas of the 7 cellists averaged on the 3 repetitions of each postural conditions, and for the two playing modes. Area statistics are given in *Detached mode (Left)* and *Legato mode (Right)*

5.2 Influences on the sound

For each of the postural conditions, we computed the acoustical features, associated to the 3 recorded repetitions of a same playing mode/tempo combination. These features were then averaged to estimate a global audio descriptor with respect to the postural condition. Finally, the postural audio descriptors were presented note by note, thanks to time onsets of the pitch curve.

Influence on rhythm. Metrical deviations are a fundamental elements of musical expressivity. The rhythmical descriptor proved to be particularly relevant for part 5 bar 1, consisting in cross-string arpeggio groups composed of 4 notes. Indeed, it revealed that the cellist made a systematic use of timing variations to communicate her interpretation of the musical structure (Fig. 6). Interestingly, we could notice that IOI deviations weren't organized in a random way, but according to rhythmical structural units. In the *normal* condition, we noticed similar adjustments in the temporal guidance of IOI deviations for each group, as if the performer tried to produce a special kind of rubato phrasing inside each group, by constantly lengthening the first arpeggio note, and accelerating the 3 remaining notes in different ways. This result confirmed many previous researches, aiming to demonstrate the spontaneous chunking of musical interpretation in shorter elements to facilitate the phrasing construction (Penel and Drake 2004).

We also discovered that the rubato phrasing of this sequence depended a lot of the playing mode and postural constraints. For example in the *detached* mode, the constraints didn't really affect the musician's expressivity, because the rubato lines roughly followed the same evolution scheme, whatever the postural condition. In the *legato* mode on the contrary, the cellist clearly had more problems in the guidance of her natural rubato while being constrained. This was particularly noticeable in the *fully-constrained* condition, with a considerable lengthening of the first arpeggio notes, and a strong incoherence of the rubato guidance, compared to the *normal* expressive situation. We also noticed a progressive harmonization of this IOI lengthening along the sequence between the *fully-constrained* and the *normal* situations. This result might be explained by an evolutionary adaptive strategy of the cellist to ensure the coarticulation process in spite of the constraint (Godoy 2013). The phenomenon, specific to the *fully-constrained* condition in *legato* playing mode, thus revealed an important role of the cellist's head to handle the global coherence in expressive timing for large bowing movements.

Influence on dynamic. Expressivity in a musical performance is largely influenced by loudness modulations. Thanks to the dynamical descriptor, we could observe strong energy variations in part 5 already investigated for timing deviations, especially visible on bar 2 (Fig. 7). Interestingly, from the RMS,deviations, we rediscovered the already existing IOI tendency: Dynamic changes don't seem to be organized in a random way, but rather follow a common wave pattern for

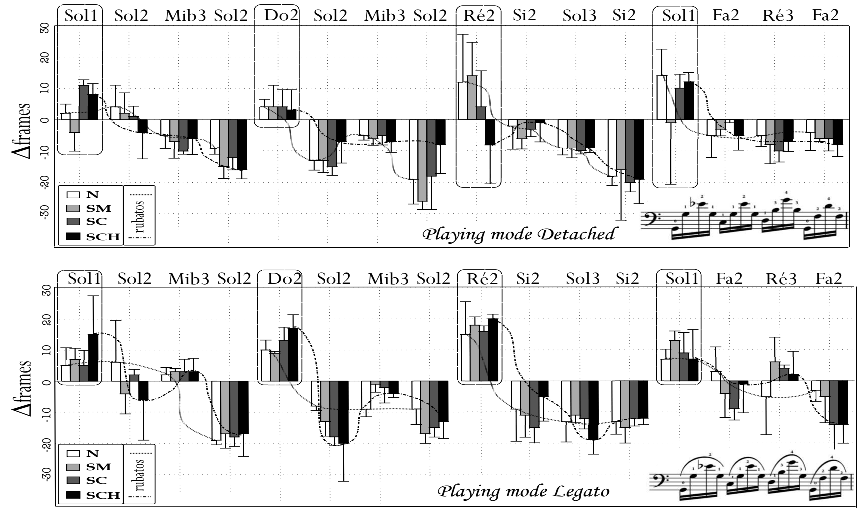

Fig. 6. Rhythmic variations computed as IOI deviations from their theoretical value, averaged on each note of part 5 bar 1, and for each postural condition. Positive deviations correspond to lengthened notes, negative deviations to shortened ones. Timing variations are shown in *(Top)* ***Detached mode*** and *(Bottom)* ***Legato mode***. Rubato guidances are specified by bezier curves.

each rhythmical unit of 4 notes. The two first notes of each arpeggio are the loudest, while the third one is the weakest, and the fourth one often initiates a rise. Again, this result supported the idea of a spontaneous chunking of musical interpretation in shorter elements, facilitating the dynamic construction in addition to phrasing. As a consequence, we could postulate that the cellist conducted the musical expressivity by synchronizing rhythmic and dynamic variations.

We discovered also that the dynamic levels of this sequence depended a lot on the playing mode and postural constraints. Indeed, the constraints caused a global dynamic decrease compared to the *normal* condition, but their effects were variable according to the playing mode. For example in the *detached* mode, the constraints didn't considerably alter the natural dynamic level, and surprisingly, this was especially true for the *fully-constrained* condition. In the *legato* mode on the contrary, the cellist clearly had more difficulties in reproducing the dynamic level while being constrained, in particular for the *fully-constrained* condition, where the dynamic levels decreased drastically. It revealed therefore the important role of the cellist's head to handle the global expressive dynamics while applying large bowing movements. Furthermore, the *semi-constrained* condition proved that the chest mobility was also important to ensure sufficient dynamic levels.

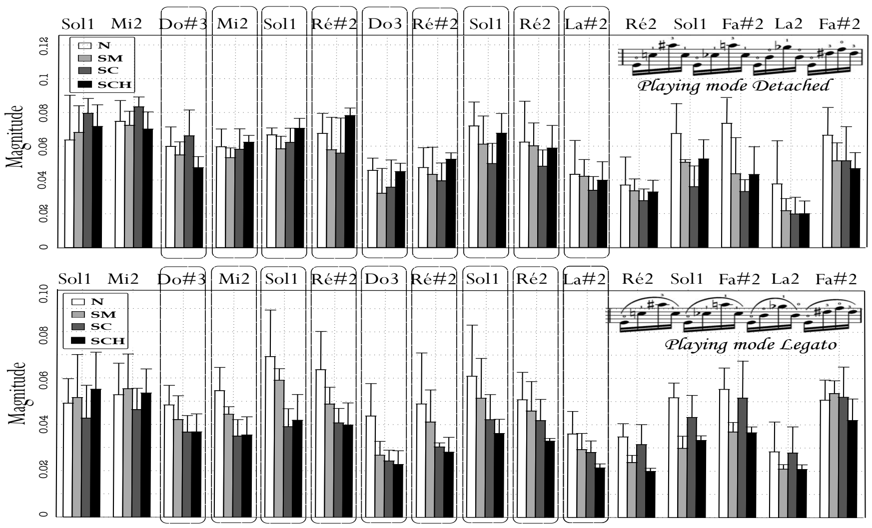

Fig. 7. Dynamic variations computed as RMS levels, averaged on each note of part 5 bar 2, and for each postural condition. Loudness changes are shown in *(Top)* ***Detached mode*** and *(Bottom)* ***Legato mode***

Influence on timbre. Timbre modulations also play an important role in the expressivity of a musical performance. For a bowed string instrument like the cello, timbral variations are particularly relevant for characterizing the quality of the interaction between the bow and the string. Hence a *round* sound will stand for a perfect bow-string interaction whereas an *harsh* sound will denote a poor contact quality. Spectral centroid analysis hardly revealed interesting effects of the postural constraints on the timbre. However, the tristimulus descriptor, and particularly the *harshness* descriptor, which presents the tristimulus coordonates in one single measure, turned out to be especially relevant for discriminating timbral sound quality across the postural constraints and playing modes. It was tested for the part 4 bar 1 of the score, consisting in fast-syncopated shifts of the left hand. As a matter of fact, we observed a high increase of the descriptor value for specific notes of the *fully-constrained* condition in the *legato* playing mode. These notes were the first ones of a syncopated group, standing for keynotes preparing and so anticipating the fastest shifts. When carefully listening to these notes, we could notice that they sounded consistently harsher, more scratchy and unfocused, compared to the *normal* condition. This result therefore revealed 2 interesting things: Firstly, the descriptor was efficient to correctly discriminate the loss of matter for each note. Secondly, it appeared that the cellist's head played a fundamental role in wide bowing, by helping anticipatory movements of the left hand without any loss of sound matter. This could be the sign of a postural support for the bilateral transfer between the 2 arms.

6 Conclusions

The influence of cellists' postural displacements on musical expressivity was investigated through a comparison of 4 postural conditions. Their effects were analyzed, as a function of *detached* or *legato* playing mode, on the global posture and the musical expressivity of a professional cellist. On the one hand, to analyze postural displacements, we estimated the 3 geometrical features of an ellipse (area, orientation and flatness), encompassing the COP (Center Of Pressure) trajectories for the system {cellist-instrument}. On the other hand, to analyze musical expressivity, we defined 3 adapted audio descriptors featuring the rhythmical, dynamical and timbral dimensions of the sound. As predicted by the hypotheses, the acoustical descriptors seemed to be relevant for our study and revealed on the whole rather important differences between the 4 postural conditions. Postural descriptors indicated some global tendencies but were difficult to generalize between the cellists.

Regarding the influence on the cellists' posture, the three postural constraints were not much affected a lot by the playing mode. This was different in normal playing, where most of the cellists reduced the amplitude of their postural displacements for *legato* mode. We might deduce that for continuous controls of wide bowings, most cellists tend to naturally immobilize their chest movements. The constraint of mental immobilization caused the decrease in amplitude of postural displacements for the majority of the musicians. This might suggest the existence of an incompressible postural quantity of movement, necessary to achieve instrumental gestures. The two physical immobilization constraints modified the natural dynamic relation existing between the cellist and the instrument, which resulted in different compensation strategies. For some of them, the postural displacements were even wider while constrained than in the normal condition. These differences are probably due to the lack of naturalness, which forces the musicians to spontaneously find new synergies to bypass the constraints. Future investigations of Mocap data should refine these conclusions.

Regarding the influence on the cellist's musical expressivity, the condition of total immobilization caused the highest rhythmical deviations, loudness and timbre modulations for specific notes in the analyzed score parts, and primarily while achieving wide bowing movements of the *legato* playing mode. In this context, it seemed that the cellist encountered difficulties in controlling the rubato coherence characteristics of an expressive phrasing. In parallel, we also noticed the strong dynamic decrease caused by these playing conditions on the natural loudness produced by the cellist. The combination of these 2 results led to the conclusion that the cellist's head mobility was an important factor for the temporal and dynamical guidance in musical expressivity. Furthermore, while requiring fast shifts with the left hand in these conditions, we noticed that the notes preparing the shifts systematically were perceived as scratchy. This result might imply that the head also plays an important role as anticipator and coordinator of arm movements. The degree of the head's freedom relatively to the spine thus seemed fundamental to ensure a fluid bilateral transfer between arms, and thus avoiding the emergence of harsh sounds.

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