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) a *normal* condition without any constraints, (b) a *mentally static* condition where the cellists were asked to keep their posture as static as possible, (c) a *physically semi-constrained* condition where the cellists' torso was attached to the back of a chair by a safety race harness, and (d) a *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 spectro-temporal features and rhythmical variations 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

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music cognition approach [12]. 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 [17]. Some studies directly investigated connections from score structure to interpretation through a note by note analysis [2,6]. Others explored the musician's body as a mediator of expressive sensitivities according to two gestural levels [3]: 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 [8,18], the piano [15], the harp [4], and the violin [16]. 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, and their influence on the musical expressivity. Some studies examined the influence of physical parameters of the cello bow on spectral features [1,5]. Others extracted coordination patterns of joint movements in the cellists' bowing arm to characterize musicality [19], or attempted to identify trends of cellists' motor process through expressive timing and dynamic audio features [9]. 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 [7]. 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 answer some of these questions, 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, would 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 present the global tendencies for all the cellists.

3.2 Scores

Design. The choice of an adequate score as support of investigation for ancillary gestures, required some thoughts. Selections from the standard cello repertoire are colored by emotional connotations, which can result in very different natural bowing and fingering 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, to achieve a common base for decoding and comparing cellists' ancillary gestures. Consequently, we designed a specific expressive score, combining short study fragments of cello suite excerpts from the Bach repertoire in which the 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 part four that corresponds to fast syncope shifts of the left hand (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 produces a single note, while *legato* mode is obtained when several notes are played by the same bow stroke. To take into account the playing modes, we designed 2 versions of the same score with different lengths of note ties. In the present study we focus on the slow tempo.

Fig. 1. Part 4 of the score: fast syncope shifts of the left hand. Two versions of this score part correspond to the two playing modes: *(a)* **Detached** playing mode, *(b)* **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} on 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) by 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 varied according to the condition, the force platform was re-calibrated between each postural session.

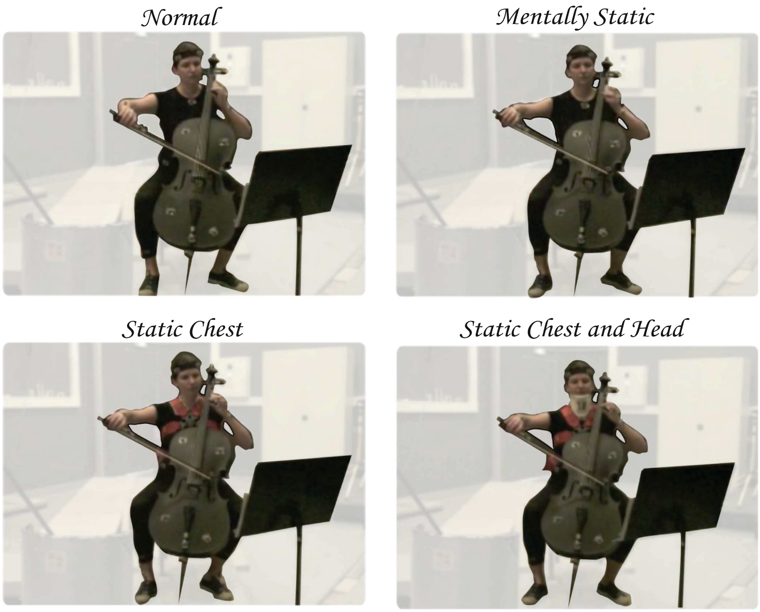

Fig. 2. The 4 postural conditions of experiment: *(TopLeft)* Normal Condition (**N**, *(TopRight)* Static Mental Condition (**SM**, *(BottomLeft)* Static Chest Condition (**SC**, *(BottomRight)* Static Chest and Head Condition (**SCH**

Design. For each postural session, the experimental design included 2 playing modes (legato/detached) × 2 tempi (slow/fast) × 3 repetitions within-subjects, resulting in 12 takes by session and by subject. The 4 experimental sessions were carried out 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 × 4 sessions = 48 trials by cellist.

Procedure. The musicians received the score before the 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 h for each cellist.

4 Descriptors

4.1 Postural Descriptors

Method. 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. To measure the general tendencies of the COP displacements, these postural descriptors were computed on the complete duration of the score, i.e. not only on part four.

COP Ellipse Area. The area of the ellipse is an estimation of the total surface covered by 95 % of the COP displacements.

COP Ellipse Orientation. The two main ellipse orientations are computed by a principal component regression on the COP centered data. This process results in a pair of orthogonal components standing for the 2 trigonometrical angles of the semi-major and semi-minor axes. The first component (the angle of the semi-major axis) characterizes the main direction of the postural displacement.

COP Ellipse 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 revealed 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).

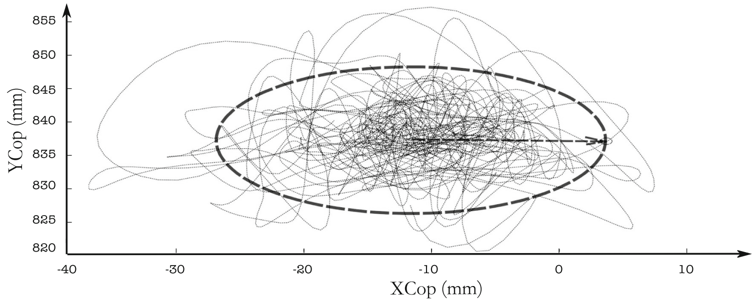

Fig. 3. Example of **Confidence ellipse** estimated from COP displacements of the system {cellist-instrument} on the force platform. The sequence is a player's trial in the *StaticChest* postural condition

4.2 Audio Descriptors

Method. The choice and design of the audio descriptors were chosen according to different zoom levels of the score part, i.e. at note level on specific notes or at beat level including a set of consecutive notes. To compute the descriptors, we first extracted the chosen note or note sequence from the audio recordings using the Praat software. Then, we adapted an audio pitch tracking algorithm from the Matlab MIR toolbox [11], in order to segment each note in the sequence. Within this process, each audio signal is divided into frames overlapped by a factor compatible with the frame rate of the mocap system, i.e. 8 ms *(1/125 Hz)*. Within this process, each audio signal was divided into frames overlapped by a factor compatible with the frame rate of the mocap system, i.e. 8 ms *(1/125 Hz)*. The pitch could then be estimated for each frame by computing the autocorrelation function of the signal spectrum and thus isolating the fundamental frequency.

Temporal and spectral descriptors were computed for each note of the sequence, on the basis of the information provided by the pitch segmentation process. The temporal descriptors were derived from the note transitions and temporal envelopes of the signal. The spectral descriptors were computed from the frequency contents at the frame level, before being averaged for all the frames encompassing each note.

Temporal Descriptors

Local Tempo Deviations. A common way to assess the finesse in phrasing consists in computing the metric or local tempo variations of each note. The computation of these variations was based on the IOI (Inter-onset interval) deviations of each note according to their theoretical durations. An IOI stands for the duration between each onset of two consecutive notes. Since there was no silence between the notes of our sequences, we roughly assimilated the IOI of a given note to its total duration. For each note n, the descriptor of IOI deviation $IOIdev$ was computed as the difference in frames between the theoretical and real durations of the note:

$$IOI_{dev}(n) = IOI_t(n) - IOI_r(n) \tag{2}$$

with $IOI_t(n)$, $IOI_r(n)$ denoting respectively theoretical and real IOIs of the note n.

Attack Slope. The classical descriptor Attack Time could have been adopted as a temporal descriptor for each note, but the Attack Slope (ATS) was preferred in the present case to overcome energy differences within a musical note sequence. For a single note n, the descriptor ATS represents the temporal increase or average slope of the energy during the attack phase [13]:

$$ATS(n) = \frac{PeakValue(n)}{AT(n)} \tag{3}$$

where AT is the Attack Time, i.e. the time it takes for the temporal envelope to deploy from 10 % to 90 % of its maximal value $PeakValue$.

Spectral Descriptors

Relative Brightness. By attentively listening to the sound recordings, we noticed certain timbre differences between postural conditions, perceived as spectral enrichments or impoverishments, that contributed to more or less metallic colorations of the sound. Hereby, we searched for an estimate of the proportion of high-frequency partials within the notes by the spectral centroid, an estimation of the barycenter of the spectral energy distribution, correlated to the perceived *brightness*. Nevertheless, this well-known descriptor is pitch-dependent and is therefore not adapted to characterize the *brightness* within a note sequence of different pitches. For this reason, we designed a relative *brightness* descriptor based on the Tristimulus criterion [14], which displays the energy distribution of harmonics in three frequency bands determined by the amount of spectral energy inside each band relatively to the total energy of harmonics. The first band contains the fundamental frequency, the second one the medium partials (2, 3, 4) and the last one higher order partials (5 and more). If a note n is composed of L frames, the tristimulus of this note constitutes three spectral coordinates, corresponding to spectral barycenters of each band:

$$TR_1(n) = \frac{1}{L}\sum_{l=1}^{L-1} TR_1(l) = \frac{1}{L}\sum_{l=1}^{L-1} \frac{A_1(l)}{\sum_{h=1}^{H} A_h(l)} \qquad (0 \leq l \leq L-1) \tag{4}$$

$$TR_2(n) = \frac{1}{L}\sum_{l=1}^{L-1} TR_2(l) = \frac{1}{L}\sum_{l=1}^{L-1} \frac{\sum_{h=2}^{4} A_h(l)}{\sum_{h=1}^{H} A_h(l)} \qquad (0 \leq l \leq L-1) \tag{5}$$

$$TR_3(n) = \frac{1}{L}\sum_{l=1}^{L-1} TR_3(l) = \frac{1}{L}\sum_{l=1}^{L-1} \frac{\sum_{h=5}^{H} A_h(l)}{\sum_{h=1}^{H} A_h(l)} \qquad (0 \leq l \leq L-1) \tag{6}$$

where $A_h(l)$ is the amplitude of the h^{th} harmonic in frame l, and H denotes the total number of harmonics taken into consideration.

From this descriptor, we designed the Tristimulus ratio (TRIratio), a more compact descriptor focusing on the spectral transfer between low and high frequencies that is independent of the note pitch and is given by the formula:

$$TRIratio(n) = \frac{TR_3(n)}{TR_1(n) + TR_2(n)} \tag{7}$$

Hence, relative energy transfers towards higher partials induce an increase in the TRIratio, resulting in sounds that are perceived as more *harsh*, metallic and brilliant.

Spectral Richness. The previous TRIratio descriptor informs us about the relative localization of spectral energy within a note. However, it doesnt necessarily provide a suitable characterization of how the spectral energy is deployed around its barycenter and how this contributes to the coloring of the sound. This information might be obtained with the Harmonic Spectral Spread descriptor (HSS), which increases when the spectral bandwidth increases, resulting in a spectrally richer sound. At the frame level, the HSS is defined as the power-weighted RMS deviation from the Harmonic Spectral Centroid (HSC), i.e. the amplitude-weighted mean of the harmonic peaks [10]:

$$HSS(n) = \frac{1}{L}\sum_{l=1}^{L-1} HSS(l) = \frac{1}{L}\sum_{l=1}^{L-1} \frac{1}{HSC(l)} \sqrt{\frac{\sum_{h=1}^{H} [(f_h(l) - HSC(l))^2 A_h(l)^2]}{\sum_{h=1}^{H} A_h(l)^2}} \tag{8}$$

where $f_h(l)$ and $A_h(l)$ are respectively the frequency and the amplitude of the h^{th} harmonic in frame l.

5 Influence of Constraints on the Postural Displacements

We here discuss the influence of the experimental conditions on the postural features of the COP ellipse across all seven cellists.

5.1 Method

For each of the 4 postural conditions, we computed the geometrical features of a COP confidence ellipse, obtained by averaging the 3 COP ellipses corresponding to the repetitions of a given playing mode (*legato/detached* at slow tempo. This yielded a set of 4 postural conditions $\times$ 2 playing modes = 8 averaged data of ellipse descriptors for each cellist. In particular, we here focused on the area descriptor of the mean postural ellipse, as it turned out to present the most interesting variations across postural conditions and playing modes. For this ellipse area descriptor, the final data set was thus composed of 7 cellists $\times$ 8 posture/mode combinations.

To assess the influence across all cellists of the factors *postural conditions* and *playing modes* on the mean ellipse area descriptor, we performed two-way repeated measures ANOVAs and post-hoc pair-wise comparisons with Least Significant Difference (LSD) procedure.

5.2 Results

Analysis by two-way repeated measures ANOVAs first revealed an effect of the playing mode, $F(1, 6) = 5.87, p = .051$. Indeed, the mean COP ellipse area was significantly greater for *detached* mode ($27\,\mathrm{cm}^2$) than for *legato* mode ($19\,\mathrm{cm}^2$). The effect of the postural condition was marginally significant, $F(3, 18) = 2.84, p = .066$. Pair-wise post-hoc comparisons revealed that the COP ellipse areas of the *Static Mental* condition were significantly lower in average ($\mathrm{SM} = 13\,\mathrm{cm}^2$) than those of the physically constrained conditions ($\mathrm{SC} = 27\,\mathrm{cm}^2$, $\mathrm{SCH} = 28\,\mathrm{cm}^2$ with $p < .05^*$), and marginally lower than the *Normal* condition ($\mathrm{N} = 24\,\mathrm{cm}^2$ with $p = .074$). Furthermore, the analysis didn't reveal any effects of interactions between the two factors.

In order to increase the precision of these results, we carried out two separate one-way repeated measures ANOVAs with the postural condition as a factor, for each playing mode across the cellists. Regarding the *detached* mode, no significant differences emerged between the mean postural COP ellipse areas ($\mathrm{N} = 27\,\mathrm{cm}^2$, $\mathrm{SM} = 15\,\mathrm{cm}^2$, $\mathrm{SC} = 33\,\mathrm{cm}^2$, $\mathrm{SCH} = 32\,\mathrm{cm}^2$ with $p = .13$). However, regarding the *legato* playing mode, the effect of the postural condition was significant, $F(3, 18) = 3.65, p < .05^*$. Associated pair-wise post-hoc comparisons reinforced the results obtained from two-way repeated measures ANOVAs. Indeed, the mean COP ellipse areas of the *Static Mental* condition were significantly lower ($\mathrm{SM} = 13\,\mathrm{cm}^2$) than the other postural conditions ($\mathrm{N} = 22\,\mathrm{cm}^2$, $\mathrm{SC} = 21\,\mathrm{cm}^2$ with $p < .05^*$, and $\mathrm{SCH} = 24\,\mathrm{cm}^2$ with $p < .05^{**}$).

5.3 Discussion

The first result of the two-way ANOVA suggested a global impact of the playing mode on the surface encompassing the cellist's postural oscillations. Figure 4 depicts more finely this impact for each of the four postural conditions across all cellists. It can be observed that the mean COP areas in the normal situation remained relatively stable between the two playing modes. Thus, most of the cellists didn't really need to adapt their corporeal displacements to the playing mode while playing normally. By contrast, the three constrained situations caused a global decrease of mean COP areas from the *detached* to the *legato*

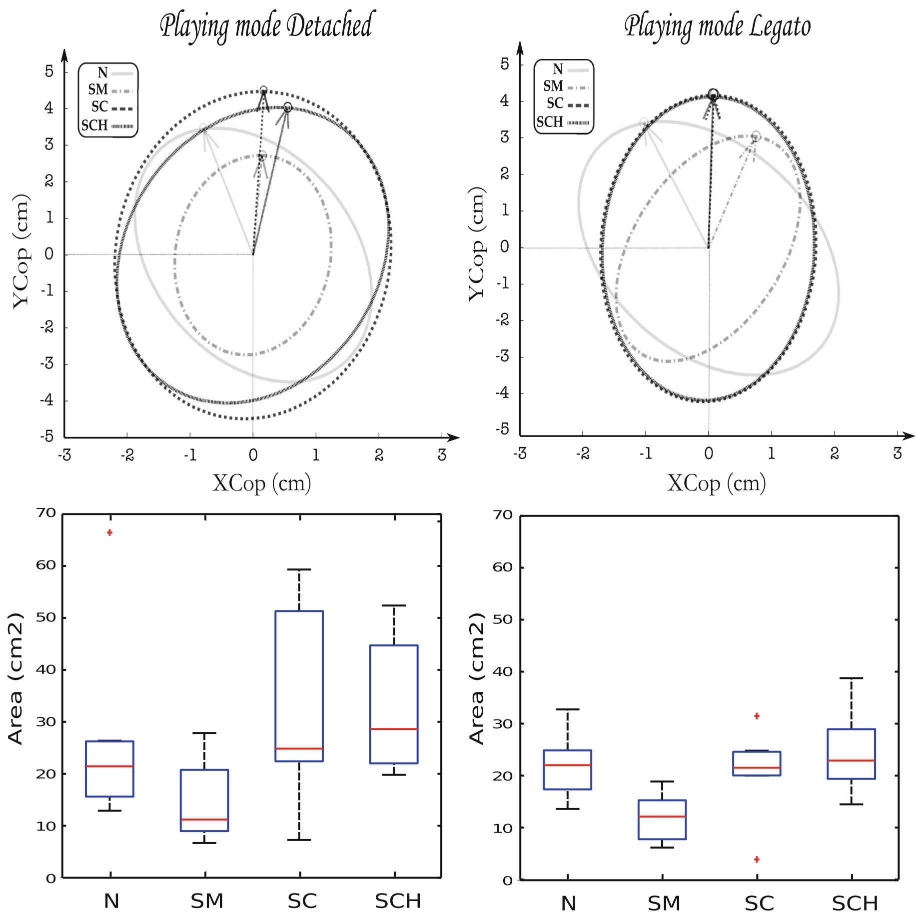

Fig. 4. *(Up)* COP ellipses averaged across the repetitions of the 7 cellists in each postural condition. *(Bottom)* Corresponding statistics of ellipse areas for each postural condition. The central lines are the medians, the edges of the boxes are the 25^{th} and 75^{th} percentiles. Mean COP ellipses and area statistics are given for the two playing modes: *(Left)* Detached mode and *(Right)* Legato mode

playing mode. This observation would suggest that on the whole, the cellists had to struggle more with the postural constraints while playing *detached*. This might seem a little bit counterintuitive at first sight, since we could expect that the musicians corporeally move more in the constrained condition when performing large bowing movements (*legato* than when they perform small ones (*detached*. However, the higher frequency of small bowing strokes might explain this difference, since within this context, the cellists might have produced a greater motor effort to make sure they succeeded each bowing transition. The broader postural displacements observed for physical immobilizations in the *detached* playing mode, might hereby reflect the cellists' effort to complete the numerous small downbow/upbow movements.

The second result suggested by the two-way ANOVA and reinforced by the 2 one-way ANOVAs, indicate that for the constraint of mental immobilization, the cellists more easily managed to reduce their postural oscillations while playing *legato* than when playing *detached*. This can actually be observed in Fig. 4. Nevertheless, in spite of their efforts, cellists couldn't completely inhibit their displacements whatever the playing mode. An incompressible postural quantity of movement always subsisted, which complies with studies on clarinetists' ancillary gestures [18]. Furthermore, in the *legato* mode, the mean COP ellipse area of the fully-constrained conditions coincides with the normal one. Consequently, these latter analyses confirm that the cellists felt more comfortable when dealing with the constraint in the *legato* than in the *detached* playing mode. From here, we could infer and discuss interesting aspects of the connection between a cellist and his/her instrument. Indeed, within a natural postural situation, this connection works as a kind of dynamical resistance. But forcing a cellist to perform with the back stuck to the chair or with an additional neck collar, breaks some elements of the musician-instrument interaction. Previous postural analyses revealed that such a situation created a discomfort felt by the musicians especially while playing in a *detached* way. Thus we can suppose that the cellists need to use more chest and head movements to produce small bowing strokes than for larger ones encompassing several notes. This observation reveals an interesting motor pattern characterizing the cellists, since a *detached* playing mode seems to involve more visible postural compensation strategies, whereas those mobilized by the *legato* process would rely on finer corporeal synergies.

The geometrical features of COP ellipses averaged across all cellists (Fig. 4) suggest other aspects relative to the influence of postural constraints. Indeed, in the normal situation, the major part of the cellists' postural displacements comprises a lateral and left-oriented component. This orientation roughly coincides with the direction in which the score has been placed. From the figure, it can be noticed that the constrained situations seem to imply an anteroposterior reorientation of the postural displacements with a slight increase of the ellipse's flatness, whatever the playing mode. This tendency is observed graphically, even though one-way repeated measures ANOVAs carried out on the features of the ellipse orientation and the flatness didn't yield to significant differences between the postural conditions. Finally, we can notice an interesting effect of the playing modes in the behavior of the two mean postural ellipses corresponding to physically-constrained situations. Indeed, they seem to coincide in the *legato* playing mode, which suggests that the head movements do not seem to improve the postural compensation within this context. By contrast, they differ in the *detached* playing mode, which may signify a more complex repartition of the roles played by the chest and the head for ensuring the postural regulation within this context. Hereby, geometrical features of the COP ellipse reinforced the previous assumptions regarding the cellists' motor patterns adapted to a given playing mode.

6 Influence of Constraints on the Musical Expressivity

We here discuss the influence of the experimental conditions on the audio features relevant for the musical expressivity across all seven cellists.

6.1 Method

For each cellist and postural condition, we computed acoustic descriptors on each note of part four for a given playing mode (*legato/detached* at slow tempo. Since the cellists performed 3 repetitions in each condition, averaged data across repetitions were considered. This yielded a set of 4 postural conditions $\times$ 2 playing modes = 8 averaged data of acoustic descriptors for each cellist. This process was achieved at a single note level and at a beat level comprising a set of four notes corresponding to the strong beat of the first musical bar of part 4 of the score (Fig. 5).

Fig. 5. The notes selected for analyzing the influence of postural constraints on the musical expressivity: Two occurrences of E3 (circles) and a group of four consecutive notes (squares). These notes are extracted from the two playing modes : *(a)* **Detached** playing mode, *(b)* **Legato** playing mode

For each one of these contexts, we assessed the influence across all cellists for the factors *postural conditions* and *playing modes* on the mean acoustic descriptors, by carrying out two-way repeated measures ANOVAs and post-hoc pairwise comparisons with the Honest Significant Difference (Tukey's HSD) procedure when possible.

6.2 Influence on One Note

The note selected for the analysis was the E3 highlighted by circles in (Fig. 5). This note occurs twice in part four, and corresponds to the first note of the strong beat within each musical bar. This note was frequently degraded across all the musicians, sounding more *harsh* and metallic in the fully-constrained postural condition, which suggests that this movement execution was hard to accomplish, even for professional cellists.

Analysis. We analyzed spectral and temporal feature evolutions for this note according to the playing mode and postural conditions, by performing a two-way repeated measures ANOVA on the averaged descriptors ATS and TRIratio (Sect. 4). This gave rise to 14 repetitions, corresponding to the 2 occurrences of E3, for each of the 7 cellists. In the end, we provided the ANOVA with a data set composed of 14 repetitions $\times$ 8 posture/mode combinations, for each averaged acoustic descriptor.

Results. The two-way repeated measures ANOVA carried out on the ATS descriptor, revealed significant effects of the postural condition, $F(3, 39) = 3.39, p = .027^{*}$, and the playing mode, $F(1, 13) = 9.73, p = .008^{**}$. Pair-wise post-hoc comparisons revealed that the Attack Slope was significantly lower in average for the fully-constrained postural condition than in the normal situation, whatever the playing mode (SCH = 0.245 and N = 0.3 with $p < .05^{*}$).

The two-way repeated measures ANOVA carried out on the TRIratio descriptor, revealed significant effects of the postural condition, $F(3, 39) = 4.31, p = .010^{*}$, and the playing mode, $F(1, 13) = 5.22, p = .039^{*}$. Pair-wise post-hoc comparisons revealed that the Tristimulus ratio was significantly higher in average for the fully-constrained postural condition than in the normal situation, whatever the playing mode (SCH = 0.33 and N = 0.27 with $p < .05^{**}$).

Discussion. The influence of the factors *postural condition* and *playing mode* on the sound descriptors can be observed Fig. 6. Interestingly, the figure reveals inverse effects of the postural condition on the temporal and spectral features of the note. Indeed, the TRIratio descriptor increases with the postural constraint whatever the playing mode, whereas the opposite effect is observed for the ATS descriptor. Furthermore, the results of ANOVA analyses revealed the statistical significance of these tendencies across all the cellists between the extreme postural conditions (normal and fully-constrained) for the two descriptors. Consequently, in the context of the note E3, the sound features are in average degraded with the postural constraint: Deprived of their postural freedom of movement, most cellists produce a shift in spectral energy towards higher frequencies (increase of the TRIratio), which results in a more metallic and *harsh* sound and apply a smoother attack (decrease of the ATS).

Note that for the *legato* playing mode, a stronger decrease of ATS and a stronger increase of the TRIratio can be observed than in the *detached* mode. This might be due to the large bowing movements used in the *legato* mode and the transition between E3 and the three following notes, that necessitates a quicker pulling of the bow on the E3 than in the *detached* mode. An interesting cross-effect of the factors also seems to emerge from Fig. 6. Indeed, for the fully constrained postural condition, the difference between the average descriptor values in the two playing modes decreases compared to the normal situation. This observation might reflect a global tendency of the constraint to limit the technical and expressive possibilities independently of the playing mode: Once immobilized, it becomes more difficult for most cellists to conserve the precise gestures needed to produce the required attack slope and the spectral features for any playing mode.

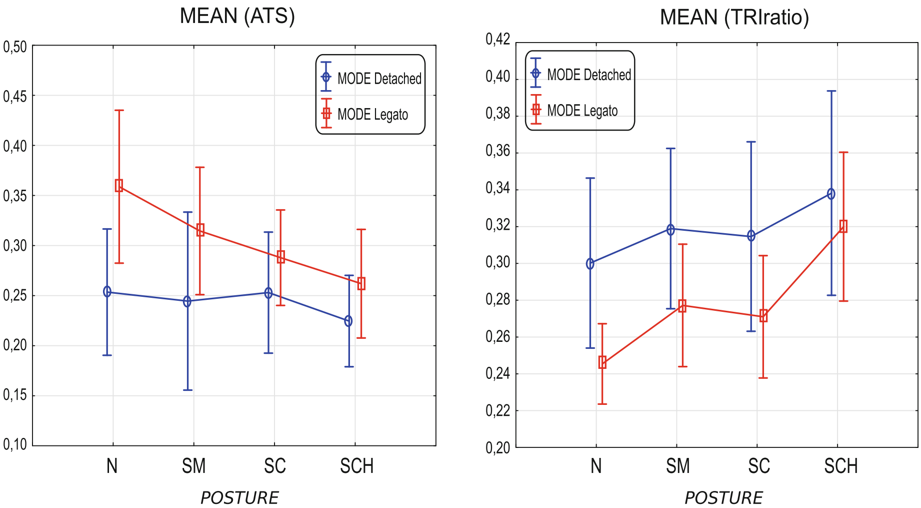

Fig. 6. Influence of the factors *postural condition* and *playing mode* on spectro-temporal acoustic descriptors analyzed for the note E3, and averaged across all the cellists: *(Left)* Temporal Attack Slope (ATS), *(Right)* Tristimulus ratio (TRIratio). The vertical bars represent confidence intervals at 95 %

6.3 Analysis of Four Consecutive Notes

A group of four consecutive notes was extracted from the examined score part. These notes compose the strong beat of the first musical bar (Fig. 5). The rhythm is based on two patterns of dotted sixteenth note followed by a thirty-second note. This musical passage turned out to be particularly difficult to play in a correct way by most cellists when posturally constrained. For all the musicians, we frequently noticed a disorganization of the natural rhythm, as well as a certain decrease of tone colors in the sequence.

Analysis. We analyzed the evolution of rhythmic and spectral features for this sequence of four notes according to the playing mode and the postural conditions, by performing a two-way repeated measures ANOVA on averaged descriptors IOIdev and HSS. This gave rise to 7 repetitions, one for each cellist. In the end, we provided the ANOVA with a data set composed of 7 repetitions $\times$ 8 posture/mode combinations, for each acoustic descriptor.

Results. The two-way repeated measures ANOVA performed on the mean values of the IOIdev and the HSS descriptors over the four notes didn't reveal any significant effect of the factors. By contrast, when applied to their standard deviation over the four notes, the obtained results became interesting.

The two-way ANOVA carried out on the standard deviation of IOIdev descriptor, revealed a significant effect of the playing mode, $F(1,6) = 18.28, p = .005^{**}$, but not of the postural condition, $F(3,18) = 2.47, p = .094$. The two-way ANOVA carried out on the standard deviation of IOIdev descriptor, revealed a significant effect of the playing mode, $F(1,6) = 18.28, p = .005^{**}$, but not of the postural condition, $F(3,18) = 2.47, p = .094$. However, when processing two separate one-way repeated measures ANOVAs with postural condition as a factor for each playing mode, the effect of the postural condition was significant, $F(3,18) = 4.86, p = .011^{*}$ in the *detached* playing mode. Further pair-wise post-hoc comparisons revealed that mean standard deviations of the IOIdev descriptor were significantly lower in the normal postural condition than in the fully-constrained one (N = 16 frames, SCH≈20 frames with $p < .05^{**}$).

The two-way repeated measures ANOVA carried out on the standard deviation of the HSS descriptor, revealed significant effects of the postural condition, $F(3,18) = 4.56, p = .015^{*}$, but not of the playing mode, $F(1,6) = 3.25, p = .12$. Pair-wise post-hoc comparisons showed that standard deviations of the HSS descriptor were significantly lower in average in the fully-constrained postural condition than in the normal condition, whatever the playing mode (N = 0.045 and N = 0.035 with $p < .05^{*}$).

Discussion. The influence of the factors *postural condition* and *playing mode* on the standard deviation of rhythmical fluctuations can be observed in the left part of Fig. 7. Metrical deviations are known to be important for the musician's expressivity. In the normal playing situation, the cellists used certain timing variations to communicate their expressive interpretation of the musical structure along the four consecutive notes. The results of the ANOVA analyses revealed that in average, the cellists tended to produce more rhythmical fluctuations between the notes while being posturally fully-constrained (approximately 4 frames more (32 ms) around the mean of their IOI deviations), than in

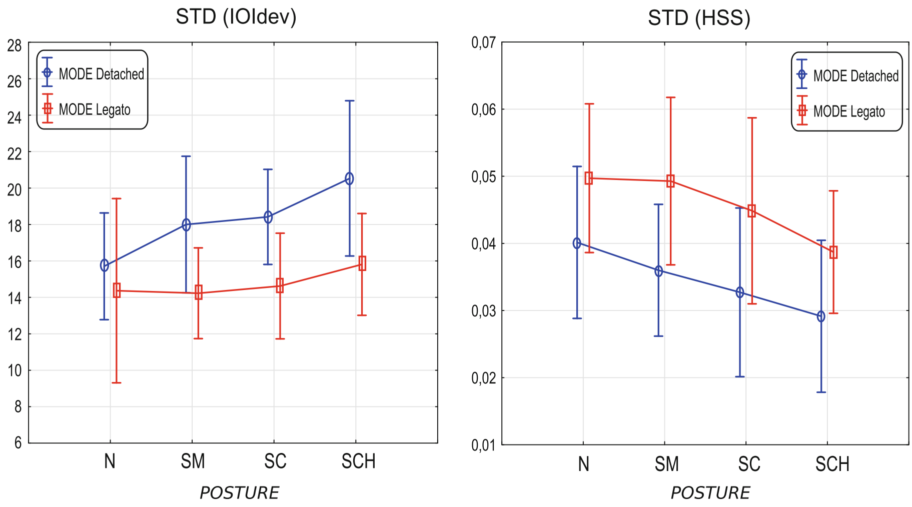

Fig. 7. Influence of the factors *postural condition* and *playing mode* on the standard deviation of rhythmical and spectral acoustic descriptors analyzed for four consecutive notes, and averaged across all the cellists: *(Left)* Inter-onset interval deviations (IOIdev), *(Right)* Harmonic Spectral Spread (HSS). The vertical bars represent confidence intervals at 95 %

the normal playing condition. It turned out to be primarily true and statistically significant for the *detached* playing mode across all the cellists. Interestingly, this result matches with a perceptual sensation of more disorganized and fragmented phrasing, as if the cellists had to struggle more with the rhythmic management when constrained. Consequently, the fully-constrained condition - and hereby the torso-head connection - might play a significant role to ensure phrasing fluidity, namely the coherency in the organization of rhythmical structural units. This deduction complies with the assumptions from the previous section, which suggested a more complex postural regulation mechanism between the chest and the head in the task of *detached* playing mode. The limitation of these natural motor pattern adjustments among cellists seems to affect the harmonious balance of their metric deviations.

The influence of the factors *postural condition* and *playing mode* on the standard deviation of spectral richness can be observed in the right part of Fig. 7. Like the IOI deviations, the timbre modulations play an important role in the expressivity of a musical performance. When freely playing, most cellists conferred an identity or a special color to each note of the sequence, which contributed to their expressivity. This feature isn't obvious to capture in a signal, because the relative amount of low or high frequencies doesn't explain alone why a tone is more colored and alive. For example, a note that sounds more *harsh* and metallic contains more energy in the high frequencies, but nevertheless does not have the ideal round color expected from a cello tone. This explains why the relative *brightness* (TRIratio) descriptor is unsuitable to capture the musical color variations. By contrast, the perceptual sensation of spectral richness within a note appears more clearly encoded in its spectral bandwidth (HSS), i.e. the spread of spectral energy distribution, since more partials are involved around the barycenter. In fact, the results of the ANOVA analyses on the HSS deviations revealed that in average, the cellists tended to significantly reduce the range of their spectral spread variations between the notes while being posturally fully-constrained, and whatever the playing mode. Besides, the *detached* mode globally presented lower spectral spread variations than the *legato* mode, which may indicate an increased difficulty in controlling the timbre color variations in a context of small bowing strokes than in the case of large ones encompassing several notes. Consequently, the torso-head connection might play a significant role to ensure the expressive modulations of timbral colors. Limiting these natural motor pattern adjustments seems to cause dull timbral colors, i.e. an impression of a more uniform musical interpretation, without life and relief.

7 Conclusions

In this paper, we investigated the influence of constraints on the postural displacements and the musical expressivity of 7 experimented cellists. The main effects of these constraints appeared on a specific part of the score, corresponding to rhythmical difficulties conceived as fast syncope shifts of the left hand. The global postural displacements were estimated through the geometrical features of a confidence ellipse encompassing the cellist's COP (Center Of Pressure) oscillations. The musical expressivity was assessed through spectro-temporal descriptors at a note level, and deviations of rhythmical and spectral descriptors at a chunk level of four consecutive notes.

The constraints caused different effects on the cellists' global postural displacements, according to the considered playing mode, *detached* and *legato*. Indeed, the musicians clearly felt more discomfort in the *detached* than in the *legato* playing mode. This tendency could be revealed by comparing their specific reactions to the three types of constraints between the playing modes. First, regarding the mentally static condition, they had in average increased difficulty to perform the task in the *detached* mode, since their mean COP areas were significantly lower than for the normal condition in the *legato* playing mode only. Then, regarding the two physically constrained conditions, they seemed in average struggling more in the *detached* mode, since their mean COP areas considerably increased, while remaining relatively stable in the *legato* mode and close to the values of the normal condition. In a nutshell, the cellists seemed to adopt more postural compensation strategies when playing *detached* than *legato*, to achieve the same tasks while constrained. Hereby, the chest and head coupling seems to be a more critical component of the cellist's posture while performing small bowing strokes on each note (*detached* mode) than larger ones encompassing several notes (*legato* mode).

The effects of the postural constraints were also clearly audible on given sound features for most cellists. Indeed, the musical expressivity declined considerably in average along the three postural constraints, with more or less sharp effects according to the playing modes. This is a tendency which could be revealed at different chunk levels of the score part. Regarding the note level, the first tone of the strong beat within each musical bar was frequently perceived as poor and deteriorated with less matter and a more metallic aspect for the fully-constrained situation. We demonstrated that this acoustic degradation corresponded to a dual spectro-temporal transformation, i.e. a decrease in attack slope of the note (ATS), combined with an increase in spectral energy in its upper partials (TRIratio). These results remained roughly valid for any playing mode across all the cellists. Moreover, we noticed a loss in the cellists' expressiveness between the playing modes in the fully-constrained situation, since the mean descriptor values ATS and TRIratio globally varied less between the playing modes than in the normal condition. Further investigations should enable to characterize this acoustic transformation more precisely by perceptual validations of the loss in sound quality perceived in this situation and currently qualified as *harshness* for bowing instruments. It would also be interesting to explore how this *harshness* phenomenon might correlate with its associated gestural features, like bowing velocity and pressure profiles, and postural descriptors.

Finally, we could highlight an influence of the postural constraints on the sound features extracted from a chunk of 4 notes. In particular, the fully-constrained condition caused a decrease of musical expressivity in the sequence, with more or less sharp effects according to the playing modes. This tendency was revealed as affecting the natural variations of rhythme and timbre color along the sequence. Regarding the rhythmic variations, the cellists unveiled in average increased difficulty to ensure fluidity and coherency of the phrasing in the fully constrained condition. Indeed, the standard deviation of the 4 successive varying note durations (IOIdev) turned out to be significantly higher in the *detached* mode for this constraint than in the normal condition. Within this context, most of the cellists couldn't prevent themselves from being disorganized and fragmenting the phrasing, a tendency that was coherent with the increase in area of their postural oscillations. Further investigations should thus enable to relate rhythmic deviations and postural features like the chest-head coupling. Regarding the variations of timbre color, the fully constrained condition reduced the timbre variations among cellists. Indeed, the standard deviation of the spectral spreads (HSS) of 4 successive notes turned out to be significantly lower in the constrained condition inducing a loss in timbre changes and color, whatever the playing mode. In addition, since the *detached* mode globally presented lower spectral spread variations than the *legato* mode, further investigations might reveal links between the loss in tone colors and the alteration of the cellists postural features like the chest-head coupling. In a nutshell, the cellists postural movements related to the chest-head coupling might be required to ensure coherent rhythmic deviations and timbre modulations.

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