An evidence of the role of the cellists' postural movements in the score metric cohesion

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Abstract. While playing expressively, cellists tend to produce postural movements, which seem to be part of their musical discourse. This article actually highlights the existence of a metric embodiment, i.e. a natural encoding of the score metric structure through specific periodicities of the musicians' postural movements. By the means of constrained postural conditions, we assess the degradation of the metric coupling between postural and bowing gestures among several cellists. Results reveal that bowing displacements should be in coherence with their postural behavior in order to ensure a correct encoding of the metric hierarchy.

Keywords: Cellist, ancillary/postural gestures, gesture-sound relationship, metric structure, musical expressivity

1 Introduction

Investigating 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 [4, 1], these non-obvious performers' movements seem to play a role in the expressivity perceived by auditors, as well as the healthy nature of musician/instrument embodiment [8, 3]. According to the theory of embodied cognition [10], the whole musicians' body is involved during an artistic expression, and continuously shaped by three kinds of factors [23] : ergonomic (adaptation to the instrument), structural (adaptation to the elements written in the score) and interpretative (construction of a personal mental representation).

In this paper, we focus on the structural factor of embodiment, by assessing subtle mechanisms of synchronization between the cellists' ancillary gestures and the score metric structure. Such a *coarticulation* process [7] was demonstrated in previous studies through reproducible ancillary patterns localized at key points of the score for pianists [2, 20] or clarinetists [14, 6]. For bowed-string instruments, it was shown that coarticulation patterns also changed according to the type of bow stroke : short / *detached* or long / *legato* [24, 18, 22, 12]. Regarding the cellists in particular, we demonstrated in a previous work the alteration of short rhythmic sections that turned out to be more salient in *detached* than in *legato* bowing mode [16].

Metric structure can be considered as a basis from which the musicians build their proper rhythmic perception. If this hierarchical organization isn't correctly integrated through suitable and distributed motor patterns, we may suppose that the cellists' musical sense of time collapses and leads to inexpressive performances [19]. As for the dancers actually, the intrinsic periodicities of cellists' motion patterns should present different levels of simultaneous synchronizations with the metric structure [21]. We can thus wonder if the slow movements of the cellists' chest or head would play a role in their natural expressiveness by intrinsically connecting to the musical time flow and the phrasing structure. Our study investigates the question by quantifying the phenomena of metric coupling between the ancillary and instrumental movements of cellists.

2 Protocol

2.1 Participants

The protocol described in this study is a subset of a larger experiment fully described in [16]. Seven cellists (4 males, 3 females) took part in this experiment. We chose musicians with high-level expertise, to ensure that any expressive degradations were due to postural constraints and not to technical weaknesses.

2.2 Apparatus

As we needed to analyze concurrently the motion and acoustic features produced by the cellists, an environment of two technological systems was set up :

– A eight-camera infrared motion-capture system (Vicon 8[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. A conversion to a simplified subset called *Dempster model* [5] was then carried out as an avatar of 20 markers corresponding to the 20 main body joints.
– A cello bridge pickup (Dpa 4096) connected to a MOTU interface (Ultralite MIC3) and configured at a frame rate of 44.1 KHz. The microphone location allowed to capture the acoustic features within the sound signal at source without being affected by potential reflections of the experimentation room. Audio and movement recordings were synchronized by means of a manual clap at the beginning of each recording.

[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`

2.3 Procedure

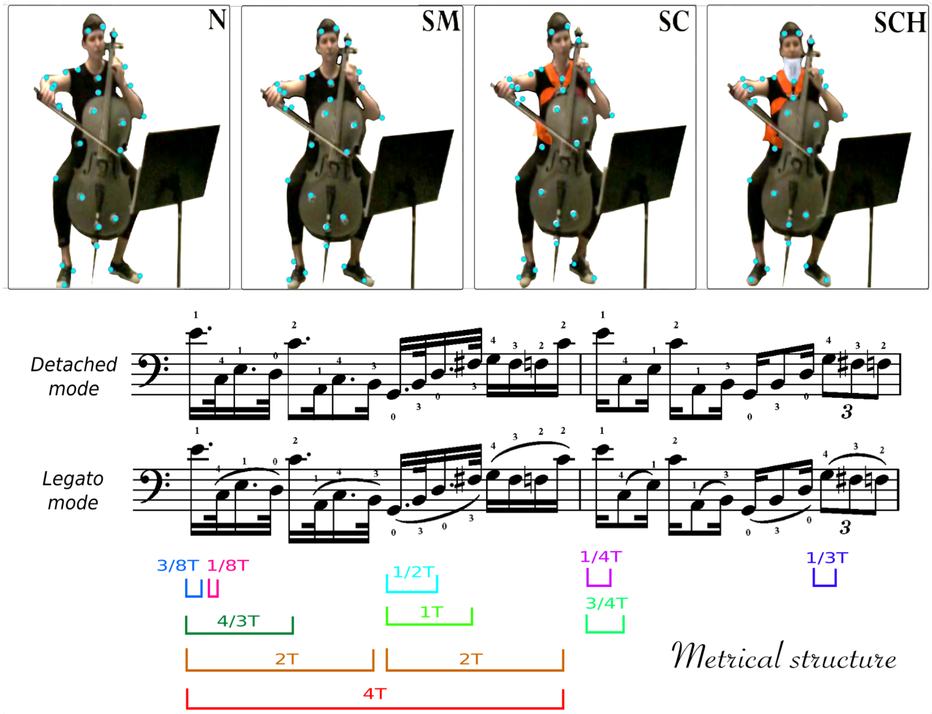

Fig. 1. The four postural conditions and the hierarchy of the score metric units

The cellists were asked to play a calibrated score at a slow tempo (♩= 45 bpm), while being subjected to four conditions of postural immobilization (Fig. 1).

- **N :** ***Normal condition***. Natural play as in a performance context.
- **SM :** ***Static Mental condition***. Stay as immobile as possible while playing.
- **SC :** ***Static Chest condition***. Physical semi-constrained situation, with the torso attached to the back of their chair by a 5-point safety race harness
- **SCH :** ***Static Chest and Head condition***. Fully constrained situation, with the torso attached as in the SC condition and a neck collar adjusted to limit head movements.

Whatever be the postural condition, they were informed to try playing in the most expressive way. The protocol also planned to assess the effect of the bowing mode (*detached/legato* for short/long bow strokes respectively), by proposing two versions of the same score with different bow stroke lengths. The cellists had to achieve three repetitions of each combination of factors (postural condition and bowing mode) given in a random order for each participant.

The score was composed of six parts targeting specific technical cello difficulties. In this paper, we focus on a part with syncopated metric patterns that was assessed by the cellists as particularly difficult to perform in the constrained postural situations. The metric structure of this part, presented in Fig. 1, has been built as a grid of ten metric levels corresponding to relative time fractions of a quarter note beat (1T = 60/45 = 1.33s at ♩= 45 bpm). Our aim here was to establish relationships between this hierarchy of score metric units and the motion periodicities encoded at different levels of the cellists' body. To achieve that, we focused on the metric behavior of three marker trajectories located on the effective gesture side (mid-point of the bow) and on the accompanist gesture side (mid-points of the torso and of the head). We also simplified the analyses by only considering these marker displacements along the medio-lateral direction (cf Fig. 2), that was found as a prominent dimension of the whole cellists' movements [17].

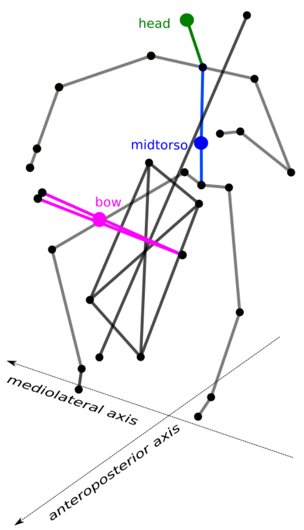

Fig. 2. The three markers considered for metric analyses

3 Analysis

3.1 Computation of a metric spectral centroid (MSC)

One way to quantify the overall metric embodied in a movement may consist in computing a centroid (or barycentre) of the metric units associated with its periodicities. To do this, it is sufficient to extract a reduced version of the frequency spectrum of the movement, containing only the amplitude peaks that correspond to the metric units listed in the score (cf Fig. 1). From this reduced spectrum, we calculated the metric spectral centroid (MSC) by applying the same type of formula as the well-known spectral centroid descriptor[15, 9]. MSC descriptor thus stands for an average of the energies contained in the spectrum periodicities weighted by their metric rank:

$$MSC = \frac{\sum_{k=1}^{K} f_k A_k}{\sum_{k=1}^{K} A_k} \quad (1)$$

where k is the metric rank and K is the total number of metric units. For a given marker trajectory, the frequencies f_k and amplitudes A_k refer to its spectral peaks computed and associated as best as possible to a list of expected metric units.

In the context of our score part, we analyzed the metric of three marker motions (*bow*, *midtorso*, *head*) through a grid of $K = 10$ predefined metric units (cf Figs. 1 & 2). This process relied on four steps involving acoustic data (steps 1 & 2) and motion data (steps 3 & 4) :

1. Estimate the average duration of the quarter note beat (1T) in the sequence, based on the "Inter-Onset Intervals" (IOIs) of the notes that compose it. For each score bar, we computed a cumulated average of its note IOIs with respect to the four beats of the bar. This estimation of a bar quarter beat was then averaged among the four bars of the sequence to get a more accurate measure.
2. Build the metric hierarchy of the sequence by multiplying the estimated quarter note beat by the ten relative fractions of its metric grid. Next pass it to the inverse to get a metric grid of frequency values.
3. Conduct an FFT analysis (*Fast Fourier Transform*) to extract the most salient motion periodicities over the sequence duration. We chose to detect the 15 highest spectral peaks, as it empirically represented a good compromise between the total number of motion frequency peaks and the number of metric units to discover.
4. Select ten motion frequency peaks (among 15) likely to be the closest ones from the established metric hierarchy of ten frequency units. In this aim, we applied a two-way algorithm on a table associating the ten metric references (the keys) to the 15 identified spectral periodicities (the values). For each sequence of marker trajectories, the program solved an optimal distribution of ten periodicity values equal to a single motion frequency or zero in case of non-matching with the metric references.

Finally, the 10 key/value pairs of each distribution were used to get an estimation of motion metric centroid (cf Eq. 1). This MSC thus characterized a global motion synchronization on the most probable metric unit of the score part. The next two paragraphs illustrate this analysis process for sequences chosen among the cellists' repetitions in the bowing modes *detached* and *legato*. For the sake of clarity, we only present them in the two opposite conditions (Normal and Fully constrained), that highlight the strongest metric differences (cf section 4).

3.2 Motion metrics for *detached* bowing mode

The Fig. 3 illustrates a representative tendency of motion metric analysis in *detached* bowing mode between the two opposite postural conditions (N and SCH) of a same cellist.

Regarding the motion trajectories of markers (Fig. 3.1), the periodicities of bow strokes seem to remain quite constant from normal to constrained conditions, whereas those of body ancillary parts (midtorso and head) switch from large patterns approximately matching the bar structure to faster oscillations synchronized with bow strokes. This suggests a natural synchronization of ancillary gestures on the slowest metrics of the score. The constraint would cause a breaking of this behavior as a stronger coupling with the instrumental gesture.

This tendency is confirmed by the motion spectral analyses (Fig. 3.2), with natural trunk periodicities (peaks at 0.18 Hz and 0.37 Hz) slowest than those of the bow (highest peak at 1.11 Hz). In the constrained situation, we actually notice a similar distribution of the bow metrics (highest peak at 1.17 Hz) in contrast with those of the midtorso and head that have increased a lot (highest peak at 1.76 Hz). Interestingly, the midtorso and head present a lot of common periodicities, but those of the head have globally higher amplitudes, suggesting a prominent role of the head in the handling of phrasing of wide musical patterns.

Such metric distributions even emerge more clearly when presented as reduced spectrums of 10 metric levels (Fig. 3.3) : From normal to constrained condition, the bow MSC remains localized on the metric level 3/4T, while the midtorso/head MSCs switch from low metric levels (2T and 4/3T) to high metric levels (3/4T and 1/2T). This sharp increase of three metrical units for both midtorso and head metric spectral centroids thus confirm a strongest coupling with the main bow metric level in situation of postural impairment.

3.3 Motion metrics for *legato* bowing mode

The Fig. 4 illustrates a representative tendency of motion metric analysis in *legato* bowing mode between the two opposite postural conditions (N and SCH) of the same cellist than previously.

Regarding the motion trajectories of markers (Fig. 4.1), the periodicities of body ancillary parts (midtorso and head) seem to match quite well those of the bow strokes in the normal condition, but desynchronize with much faster oscillations in the constrained condition. In contrast to the *detached* bowing mode, this suggests a uncoupling effect of the postural constraint, i.e. a natural accompanist and supportive role of the trunk movements for slow metrics of bow strokes, that became out of sync with the instrumental gesture in situation of postural impairment.

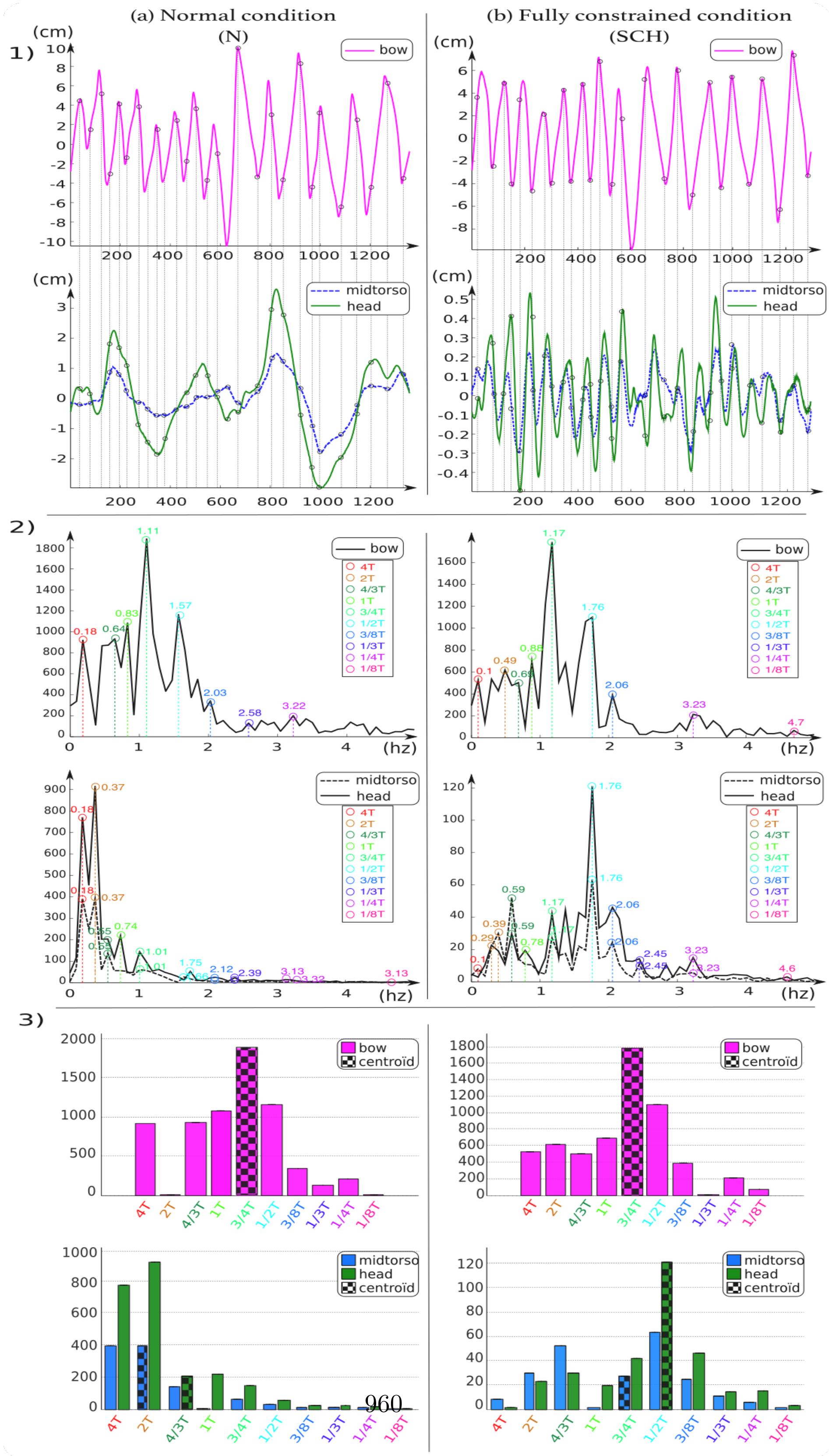

Fig. 3. Illustration of MSC computation for three markers of a cellist in ***detached*** bowing mode. **1)** Displacements along the medio-lateral direction (the vertical boundaries correspond to the IOIs of each note). **2)** Spectral analyses of these marker displacements (the 10 metric units of the score are matched to their detected periodicity peaks). **3)** Metric distribution and MSC localization of each marker between the two opposite postural conditions (N and SCH).

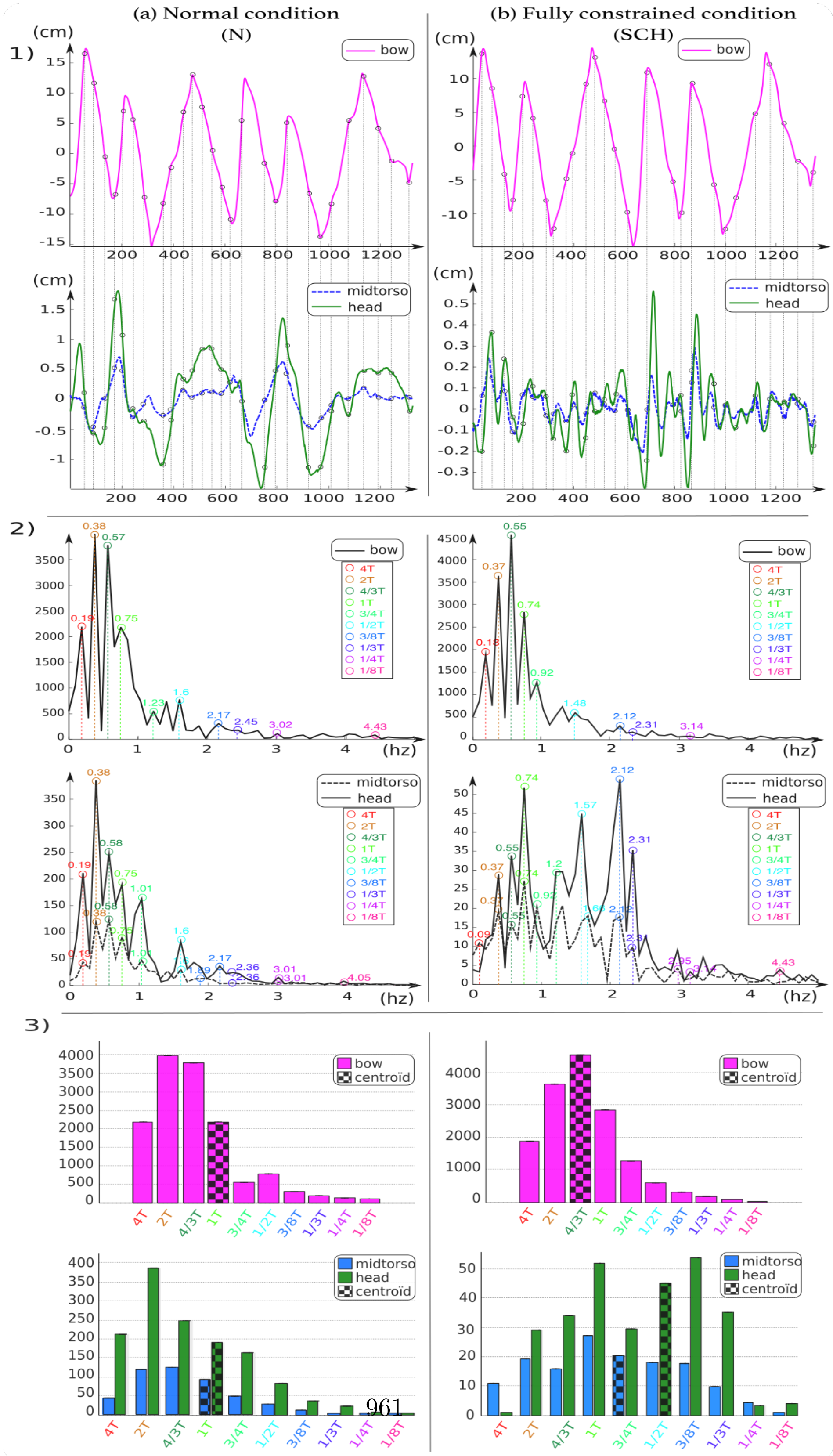

Fig. 4. Illustration of MSC computation for three markers of a cellist in ***legato*** bowing mode. **1)** Displacements along the medio-lateral direction (the vertical boundaries correspond to the IOIs of each note). **2)** Spectral analyses of these marker displacements (the 10 metric units of the score are matched to their detected periodicity peaks). **3)** Metric distribution and MSC localization of each marker between the two opposite postural conditions (N and SCH).

This tendency is confirmed by the motion spectral analyses (Fig. 4.2), with common periodicities between the trunk and the bow in normal condition : peaks at 4T (0.19 Hz), 2T (0.38 Hz) and 4/3T (0.5 Hz). In the constrained condition by contrast, the bow metric distribution seems to remain quite similar (highest peak at 0.5 Hz), whereas the postural encoding of the slowest score periodicities totally disappeared, increasing a lot towards smaller metric units : 1/2T (1.57 Hz) and 3/8T (2.12 Hz).

Such metric distributions even emerge more clearly when presented as reduced spectrums of 10 metric levels (Fig. 4.3) : Interestingly, they reveal that MSC localizations of the bow and trunk markers in the normal condition synchronized on the same metric level of a quarter note beat (1T). The constrained condition broke this natural metric coupling, since the bow MSC slightly decreased on the previous metric unit (4/3T), while the trunk MSCs increased on the next two units (3/4T and 1/2T for the chest and the head respectively).

4 Results

4.1 Generalization of the motion metric tendencies

To assess if the previous observations can be generalized to all the cellists, we conducted an analysis of variance (ANOVA) by repeated measurements over all their kinematic sequences. Such a technique is likely to quantify the inter-cellists stability of the metric centroid descriptor (MSC) of each marker through the two bowing modes and the four postural conditions. Simultaneously applied on the thee selected markers (*bow,midtorso,head*), this analysis becomes a multivariate anova (or MANOVA) of three dependent variables with two factors : [Postural condition] and [Bowing mode].

This MANOVA essentially reveals a significant effect of the postural condition factor ($F_{3,18} = 18.08; p < 0.05^{***}$) between the three MSC markers, regardless of the bowing mode. In Fig. 5 (*at left*) actually, we can first observe that for the natural condition, the MSCs of the three markers are metrically synchronized (between 0.9 and 1 Hz), in average on both bowing modes. Then, an interesting phenomenon occurs as the postural constraint increases: the MSC of the bow marker remains stable, while the MSCs of the trunk markers (chest and head) increase together, up to 1.4 Hz in the fully-constrained situation. Post-hoc LSD (Least-Square Differences) tests confirm significant MSC differences between the bow and the trunk markers for each of the three postural immobilization constraints. In the case of physical immobilization constraint by the chest alone, we also find a significant MSC difference between the torso and head markers.

The two-way repeated measures MANOVA didn't reveal significant MSC effects by bowing mode across the postural conditions. In Fig. 5 (*at right*) however, we can observe an interesting difference between the two bowing modes likely to confirm that the motion metric tendencies of section 3 can be generalized. Actually, the bow metric stability across the four postural conditions occurs around 1.2 Hz in *detached* bowing mode versus 0.75 Hz in *legato* bowing mode. As the mean trunk metric increases in the same way whatever be the bowing mode, we globally get a situation of bow/trunk metric coupling (respectively uncoupling) in the *detached* (respectively *legato*) bowing mode as the postural constraints reinforce.

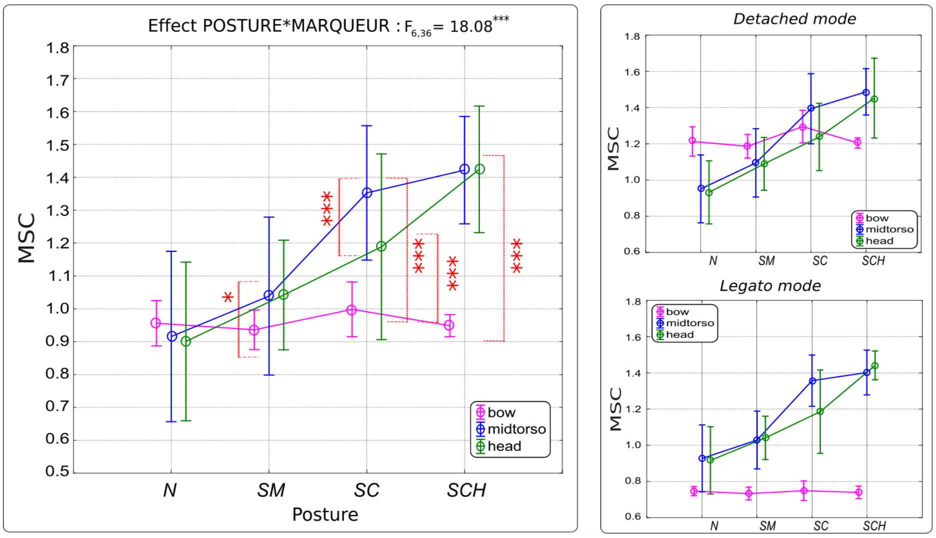

Fig. 5. MANOVA applied on the metric centroid descriptor (MSC) of three markers (*bow, midtorso, head*), according to the factors [Postural condition / Bowing mode] and performed by repeated measurements on the repetitions of the seven cellists

4.2 Discussion : the motion metrics cohesion

The results provided by MANOVA highlight a loss of the natural ***metric cohesion*** between the trunk and the bow motions as the postural constraints increase. Actually, the context of metric cohesion is reflected by the normal condition as a grouping of the metric mean values for the three markers (*bow, midtorso, head*). Then, a gradual desynchronization of the trunk metric with respect to the bow emerges from mental immobilization (SM), continues to expand by affecting more the chest than the head in partial immobilization (SC), until reaching a maximum in fully-constrained situation (SCH) for both chest and head. We here suggest that this phenomenon traduces a progressive disembodiment of the metric structure intrinsically encoded within the displacements of the cellists' segments : metric alterations would thus reflect different degrees of disorganization among the musicians' motor units.

Such results are consistent with the principles of embodied cognition, that predict different levels of metric encoding within the musicians' or dancers' body [21, 13, 11]. According to these principles, metric units of the musical structure are encoded in body segments of proportional size : the trunk, that is a large segment, should encode the largest, i.e. the slowest, metric units. In contrast, the hand holding the bow is a small body extremity, that should encode smaller and faster metric units. Our experiment shows that the more the musicians' trunk is impaired in its displacements, the more it synchronizes with metric units too high (and too fast) for its natural behavior. Such an inconsistency of the cellists' motor units didn't prevent them from ensuring the bow metric required by the score, but the produced musical stream actually seemed more tense and mechanic, as played with a strict metronome pulse. This assumption is supported by the acoustic perception of the cellists themselves when interviewed about the loss of their natural sense of phrasing.

5 Conclusion

In this paper, we proposed a methodology to match the motion periodicities of the cellists' body segments with the metric units, pre-determined by the structure of the score. Postural constraints were used to assess the metric role of specific motor units such as the chest and the head, that indirectly contribute to the musicians' expressivity. Our analyses reveal that both of these ancillary body parts would play an important role to encode the slowest metric units of the score relating to musical phrasing. Impairing them actually resulted in losses of cohesion with the bow metric that reinforced with the postural constraint. The consistency and reproducibility of this phenomenon among the cellists allow to conclude that the musicians' postural flexibility is a key ingredient of their metric embodiment.

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