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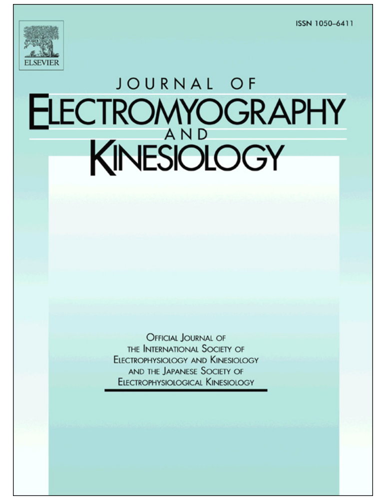

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Spatial Distribution of Surface EMG on trapezius and lumbar muscles of Violin and Cello Players in Single Note Playing

Babak Afsharipour[1,2]*, Francesco Petracca[2], Mauro Gasparini[3], Roberto Merletti[2]

1. Sensory Motor Performance Program, Rehabilitation Institute of Chicago and the Department of Physical Medicine and Rehabilitation of Northwestern University
2. Laboratory for Engineering of the Neuromuscular System (LISiN) Department of Electronics, Politecnico di Torino, Torino, Italy
3. Department of Mathematical Sciences, Politecnico di Torino, Torino, Italy

*Corresponding Author 1:

***Babak Afsharipour**

Rehabilitation Institute of Chicago
345 East Superior Street, Room 1433
Chicago, IL 60611
babak.afsharipour@northwestern.edu
Tel: +1 312 238 65 05

Francesco Petracca

LISiN - Politecnico di Torino
Via Cavalli 22/h
10138 - Torino, Italy
Tel: +39 011 090 7756
fra.petra.fp@gmail.com

Mauro Gasparini

Dipartimento di Scienze Matematiche "G. L. Lagrange"
Politecnico di Torino, Corso Duca degli Abruzzi 24,Torino, Italy
mauro.gasparini@polito.it

Roberto Merletti

LISiN - Politecnico di Torino
Via Cavalli 22/h
10138 - Torino, Italy
Tel: +39 011 090 7756
roberto.merletti@polito.it

Abstract

Musicians activate their muscles in different patterns, depending on their posture, the instrument being played, and their experience level. Bipolar surface electrodes have been used in the past to monitor such activity, but this method is highly sensitive to the location of the electrode pair. In this work, the spatial distribution of surface EMG (sEMG) of the right trapezius and right and left erector spinae muscles were studied in 16 violin players and 11 cello players. Musicians played their instrument one string at a time in sitting position with/without backrest support. A 64 sEMG electrode (16x4) grid, 10mm inter-electrode distance (IED), was placed over the middle and lower trapezius (MT and LT) of the bowing arm. Two 16x2 electrode grids (IED=10mm) were placed on the left and right erector spinae muscles. Subjects played each of the four strings of the instrument either in large (1bow/s) or detaché tip/tail (8bows/s) bowing in two sessions (two days). In each of two days, measurements were repeated after half an hour of exercise to see the effect of exercise on the muscle activity and signal stability. A "muscle activity index" (MAI) was defined as the spatial average of the segmented active region of the RMS map. Spatial maps were automatically segmented using the watershed algorithm and thresholding. Results showed that, for violin players, sliding the bow upward from the tip toward the tail results in a higher MAI for the trapezius muscle than a downward bow. On the contrary, in cello players, higher MAI is produced in the tail to tip movement. For both instruments, an increasing MAI in the trapezius was observed as the string position became increasingly lateral, from string 1 (most medial) toward string 4 (most lateral). Half an hour of performance did not cause significant differences between the signal quality and the MAI values measured before and after the exercise. The MAI of the left and right erector spinae was smaller in the case of backrest support, especially for violin players. Back muscles of violin and cello players were activated asymmetrically, specifically in fast movements (detaché tip/tail). These findings demonstrate the sensitivity and stability of the technique and justify more extensive investigation following this proof of concept.

Keywords: High density surface electromyography (HDsEMG); surface EMG; musicians; trapezius; erector spinae; violin; cello; string players

INTRODUCTION

Musicians perform daily intensive repetitive tasks and may suffer from Repetitive Strain Injuries (RSI) and develop Playing-Related Musculoskeletal Disorders (PRMDs) after some years (Zaza, 1998). Optimal playing technique avoids unnecessary effort and muscle co-contractions (Fjellman-Wiklund et al. , 2004b). In 2003, Berque studied the influence of neck–shoulder pain on trapezius muscle activity among professional violin and viola players (Berque, 2003). He reported a higher trapezius muscle activity in pain-free subjects compared to subjects experiencing neck–shoulder pain, specifically when the pain-free subjects were progressing from the rest condition to performance of a difficult piece. Furthermore, Berque observed that, at rest, the subjects affected by PRMD showed higher upper trapezius muscle activity than the pain-free subjects.

Fjellman-Wiklund (Fjellman-Wiklund et al. , 2004a, Fjellman-Wiklund, Grip, 2004b) did not find significant differences between the trapezius muscle activation of 12 violinists after an 8-week training program and a reference group. The training group perceived positive changes in breathing, muscular tension, postural control, and concentration.

Wales (Wales, 2007) assessed muscle activity in the right anterior deltoid, biceps brachii, and triceps brachii and found significant differences across the strings being played and between novice and experienced violin players. Out of the muscles assessed, Wales also found that the deltoid muscle was the most active and it displayed a pattern of constant activation to maintain shoulder abduction.

Levy (Levy et al. , 1992) compared the EMG amplitude of the upper arm muscles recorded from 15 violin players with and without a shoulder rest under three conditions (hold the violin and play two short musical sessions). The results revealed a significant reduction of the EMG amplitudes of the left trapezius and right sternocleidomastoid muscles when the shoulder rest was used.

All the studies mentioned above were carried out with bipolar electrodes which measured EMG amplitude in only one location.

The first objective of this work was to investigate the capability of the High-Density surface EMG technique (HDsEMG) to study the distribution of sEMG on back muscles of healthy musicians, in order to explore HDsEMG applicability, suitability, and limitations in this field.

The second objective of this work was to show that differences (if any) in muscle activity distribution during playing individual strings can be reliably detected by HDsEMG and mapped into sEMG images.

METHODS

We mapped the spatial distribution of sEMG activity of the mid and lower trapezius and part of the upper trapezius (right side) and erector spinae muscles of both violin and cello players. The right trapezius muscle was chosen because a) it is a relatively easy muscle to study non-invasively, b) it plays a significant role in playing the violin and cello (bowing arm) and, c) it is a target muscle for pain in PRMDs. The trapezius is a large superficial muscle that extends longitudinally from the occipital bone to the lower thoracic vertebrae and laterally to the spine of the scapula (Kendall, 2005). The lower part of the upper trapezius (UT) and the middle trapezius (MT) (jointly referred to as MT) retract/medialize the scapula while the lower trapezius (LT) depresses it. Only the right trapezius was investigated in this study to test its role in playing different strings of violin and cello.

Movement of the right arm (bowing) involves both right and left erector spinae (RES and LES) muscles which are also targeted by PRMDs. We recorded sEMG signals and obtained amplitude maps from the RES and LES muscles to test a) the detectability of small changes of muscle activity with the HDsEMG technique and, b) the effect of backrest support while playing individual strings. Furthermore, the level of proficiency was considered as a potential factor determining the ES activity during a performance. The spatial distribution of the sEMG activity and its dependence on the played string, the playing technique, and the posture, were assessed before and after 30 min of exercise to test the quality and changes of the signals and the stability of the contacts following the exercise.

We applied a 16x4 grid over the trapezius and two 16x2 grids over the left and right erector spinae muscles (with an inter-electrode distance of 10 mm and the distal electrodes at the L5 level) while playing single strings.

A. Subjects

Sixteen violin players (including three professionals and thirteen students) and eleven cello players (including three professionals and eight students) participated in this study. All subjects were healthy and pain-free and gave written informed consent. Subjects younger than 18 years provided informed consent from their parents. Table 1 summarizes the demographic data of the participants.

Table 1: Demographic data of participants in the study. For the professional players, the values are reported and for the student players mean ± standard deviation.

Characteristics	**Violin players**		**Cello players**	
	Professionals	**Students**	**Professional**	**Students**
Number of participants	3	13	3	8
Age (years)	61, 42, 58	25 ± 14	52, 55, 62	26 ± 18
Experience (years)	48, 30, 45	11.3 ± 4	40, 46, 49	6.5 ± 2
Body mass (kg)	110, 75, 70	61.8 ± 15	95, 62, 88	54.4 ± 16
Height (cm)	180, 180, 170	167.3 ± 6	179, 176, 186	163.4 ± 13
BMI (kg/m^2)	33.2, 23.1,24.2	21.96 ± 4	29.7, 20.0, 25.4	19.9 ± 3
Gender (M-F)	3-0	5-8	3-0	3-5

B. Muscles of interest and subject posture.

Surface EMG was recorded from the caudal part of the upper trapezius (UT), the middle (MT) and the lower trapezius (LT) muscles of the right side, from the left and right erector spinae (LES and RES) muscles while playing individual strings of violin and cello. Subjects played their instrument in sitting position, with and without backrest support.

C. Measurement Protocol

The spatial distributions of sEMG signals over trapezius and erector spinae muscles of both violin and cello players were studied in three different activities separated by one-minute rest.

- Large bowing: the total length of bow slides down on the string and comes back up to the starting position. Each bow (up or down) lasts 1s (bowing speed = 1 bow/s for 10s, 5 bows up, 5 bows down).
- Detaché tail bowing: bowing starts from the tail of the bow, then the bow slides shortly up and down (about 2-5 cm) on an instrument's strings. It is repeatedly done (about 8 bows/s for 10s).
- Detaché tip bowing: bowing starts from the tip of the bow, then the bow slides up and down (about 2-5 cm) on a string repeatedly (about 8 bows/s for 10s).

All aforementioned bowings started from bowing down. These bowing movements were selected because they are very common and easily repeatable by students. Subjects were asked to play the four strings sequentially. The first string (#1) was the most medial string, and the most lateral string was #4. Subjects played the strings first without backrest support and then leaning on the backrest of a chair. All movements were repeated after 30 minutes during which the subjects played a “difficult” piece of music of their choice to test the effect of half an hour exercise on the muscle activity as well as the stability of the detection system and signal quality after exercise.

A metronome set to 60 beats/min was used to control the speed of bowing. To verify the frequency of the fast movements (detaché tail and tip bowings), a video camera recorded the subject’s performance during the whole experimental session. If the number of bowings was not correct, the subject was asked to repeat the performance. A LED light was switched on at the beginning of each recording and generated a spike on the EMG signals for their subsequent synchronization with the movie.

In all, 48 sets of signals were recorded for each subject in one session (four strings, three bowing types, two sitting conditions, before and after exercise; 10s duration each). Two recording sessions were conducted on different days to test repeatability.

The order of recordings was the same for all subjects and was repeated before and after 30 min exercise in the first and second day.

Fig. 1 shows a summary of the protocol explained above.

Figure 1 about here

D. EMG acquisition

Surface EMGs were collected from the right MT and LT using a 64-electrode flexible grid with circular electrodes (Ø=3mm) arranged in 16 rows parallel to the scapular spine and 4 columns parallel to the spine with 10mm distance (IED) (Fig. 2a). The electrode arrays were manufactured in the Lab for Engineering of the Neuromuscular System (LISiN). Based on the literature recommendations for recording sites of sEMG (Barbero et al. , 2012), we localized the innervation zone (IZ) and marked it on the subject's skin. The IZs were localized using a linear electrode array (16 electrodes, IED=5mm) placed on the line connecting the C7 and acromion over the skin above the upper-middle trapezius. For the lower trapezius, the IZs were marked along two lines parallel to the C7-acromion line, but 8cm and 16cm caudally. All IZs were identified through online visual inspection of the sEMG signals in single differential configuration along the fiber directions, before grid placement. Usually, we found one IZ for the middle trapezius and one or two for the lower trapezius. The electrode grid was placed medially with respect to the IZ with the upper row aligned with the C7-acromion line, to cover both muscle compartments (MT and LT, see Fig. 2a). The grid covered mainly the MT and part of the UT muscle, but we refer the obtained activity to the MT because the edge between the two muscle portions is controversial.

Since the fibers of the ES muscles are short (from one vertebra to the next or to the second next), there is no preferred region. We placed two 16x2 electrode arrays (IED=10mm) laterally to the lumbar spine with the distal row at the level of the superior iliac spine as these sites are recommended for sEMG recordings (Barbero, Merletti, 2012). The two columns of the detection system on the lumbar muscles were parallel to the spine. The skin under the detection grids was slightly abraded with abrasive paste and rinsed with water to remove flaky residuals.

The grids were fixed to the skin using double adhesive foam with holes filled with conductive gel. Signals were acquired in monopolar configuration by EMG-USB amplifier (LISiN and OT-Bioelettronica, 128 channels, sampling frequency of 2048 Hz, a gain of 2000, band-pass filter [10-750] Hz, 12-bit A/D converter, and 1µV_{RMS} noise). An Ag/AgCl electrode (Kendall, Diameter=15mm) was placed over C7 as the reference point.

E. Pre-processing setup

Pre-processing was performed offline using Matlab 7.1. Band pass digital filtering [20-450] Hz, (by zero-lag Butterworth 2nd order filter in each direction) and spectral interpolation (to reduce power line interference up to 10 harmonics) (Mewett et al. , 2004) were applied to each recorded signal. “Bad channels” (Marateb et al. , 2012, Merletti et al. , 2013) (up to 5% of total channels in each recording), found through visual inspection, were removed and replaced by the spatial average of the neighbors (up to 8 adjacent electrodes).

The propagation of motor unit action potentials was clearly seen along the fiber direction in single differential (SD), obtained as the difference between adjacent electrodes along the muscle fiber direction, signals. Root Mean Square (RMS) maps were computed from the SD signals. For each recording (10 s duration) the RMS maps were computed from the 10 non-overlapping 1s epochs (10 maps). Each pixel (x,y) of the map represents the RMS in time of the $EMG(x,y)_i$ differential channel as in Eq. (1).

$$RMS(x,y) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} EMG(x,y)_i^{\,2}} \qquad \text{eq.(1)}$$

N is the total number of samples in the chosen epoch (1s = 2048 samples).

A region of activity (ROA) was identified automatically applying the watershed segmentation algorithm (Afsharipour et al. , 2014, Vieira et al. , 2010), as the area including the highest RMS values. Watershed (Vincent and Soille, 1991) is a region-based segmentation method which identifies the location of ridges (watersheds) in the grayscale image and labels each catchment basin (a group of pixels), surrounded by such ridges, with a different number. In the case of EMG images, the catchment basins correspond to regions of either low or high EMG amplitude, whereas watershed lines correspond to transitions from low/high to high/low amplitudes in the image. To avoid over-segmentation we smoothed the gradient of the EMG image by flattening sharp transitions of the gray intensity of the gradient image (Vieira, Merletti, 2010). These operations reduce the number of regional minima generated by the watershed segmentation method.

The spatial average of RMS values found inside the ROA(s) for each map was computed and defined as muscle activity index (MAI). The term Muscle Activity Index (MAI) is used in this work to convey the information regarding spatial average of RMS values within the ROA found by automatic sEMG map segmentation. Since normalization is difficult for the muscles under investigation, the MAI value is expressed in μV and is not normalized. This implies that comparisons are meaningful across conditions within each subject and not across subjects who may show different MAI values because of anatomical factors (e.g. different subcutaneous tissue thickness).

Figure 2 about here

F. Statistical analysis

This work is a "proof of concept" study; we aim to demonstrate that meaningful differences in spatial distribution of muscle activity can be detected with the proposed technique, but further confirmatory studies will be needed to classify conditions or subject groups. The objective of the statistical analysis was to verify that different MAIs are associated with different conditions; statistical comparison of different instruments or subject groups is outside scope of this work. The MAI data were analyzed using the R software. A linear mixed model analysis was carried out considering “muscle,” “string number,” “bowing type,” “backrest support” and “exercise” as factors and “subject” as a random additive effect. The random additive effect "subject" has been included in order to cluster together all observations and differences pertaining to the same subject.

Since the comparison between before and after the 30 min exercise (see Results) did not show a significant change in the MAI, the factor “exercise” was excluded from the analysis, and two replicates of the same measurements (before and after the exercise) were used to fit the model. The repeatability of the results was quantified by performing two identical recording sessions on two different days by computing the intraclass correlation coefficient (ICC). ICC captures the relative reliability of the measurements technique (Atkinson and Nevill, 1998). ICC computations were based on the definition and the algorithm used by "R" software using the “irr” package (Gamer et al. , 2012), for MAIs values obtained over epochs of 10s in day 1 and day 2. The computed ICCs represent a measure of agreement between the MAIs of day 1 and the MAIs of day 2 for the instruments (violin and cello) and the combination of muscle and string (see Fig. 3 in the Results). Based on the afore-mentioned linear mixed model parameters, contrast analysis and 95% confidence intervals (CI) were used to test the sensitivity of the technique to different factors such as the string, bowing type, and backrest effect (see Fig. 6 in the Results). We do not provide p values since ANOVA or statistical tests on the difference of means were not formally applied due to the limited number of subjects with respect to the relatively large number of conditions being tested. However, if the interval corresponding to 95% confidence of a MAI difference between two conditions does not include the zero value, such difference is potentially significant, and this hypothesis should be further explored in subsequent confirmatory studies with a greater number of subjects.

RESULTS

Fig. 2a shows the position of the electrode grids on MT, LT, RES, and LES muscles for both violin and cello players.

Violin players

Fig. 2b depicts raw monopolar sEMG signals from the right MT-LT and single differential signals from the RES arrays. Lack of evident propagation in the right panel of Fig. 2b indicates short fiber length.

Fig. 2c shows an example of the RMS maps of single differential (SD) sEMG signals from the MT and LT for 10s of recording during violin playing. Each map includes 8x3 pixels for each compartment of the trapezius (MT and LT). Each color map represents the RMS values (see eq.(1)) computed over 1s epoch window of SD sEMG signals corresponding to a complete bowing down to tip (odd seconds) or up to tail (even seconds).

In the upper part of the MT, at the edge with UT, higher RMS values are observed in bowing up comparing to bowing down. In all violin players, higher activity was seen at the upper portion of the MT (likely extending into the UT where the double neck curvature complicates the application of the array), while the caudal portion of the LT included higher RMS values with respect to its upper portion. In general, the MT activity map showed RMS values twice those of the LT (Fig. 2c).

Fig 3 shows the ICC values computed for the violin and cello players related to different muscles (MT, LT, RES, and LES) and strings (1-4) of the instrument. ICC was obtained for the MAI values of each muscle (computed over 10 s epochs) in day 1 and day 2. Fig. 3a shows that for the violin players the ICC is fairly high for all muscles and strings ($0.793 \leq ICC \leq 0.987$), while is lower for the cello players ($0.604 \leq ICC \leq 0.955$).

Figure 3 about here

Fig. 4a-b show the changes of the MAI of the MT and LT with respect to the string number and bowing up and down in large bowings, for both students (solid line) and professional violin players (dashed line) in the first session of recording, without backrest support. Generally, the MAI changes with respect to the string that is played. There is an increasing trend for the MAI from string 1 toward string 4 and higher MAI when bowing up with respect to bowing down. This trend, associated with the bowing direction, is not as evident in the LT.

Figure 4 about here

Fig. 4c-f shows the MAI of the ES muscles while playing fast movements (detaché tail and detaché tip) for all violin players. Detaché tail implied a higher MAI for the RES muscle compared to the LES muscle. This asymmetry in the spinae muscles is not evident in the detaché tip, where the muscle activity is more balanced between left and right. We also observed a potentially significant difference (see section F of Methods) between the MAI with and without backrest condition for both LES and RES during detaché tip and tail (Fig. 4c-d-e-f). All the aforementioned differences are summarized in Fig. 6a where the 95% CI for the respective contrasts are shown. CIs on one side of the zero level line indicate a potentially significant difference in the corresponding comparison. MAI values obtained from the second session were not significantly different with respect to the first and statistical analysis conducted separately on the two sets of measurements showed CIs consistent with each other, as shown in Fig. 6a (solid and dashed bars).

Cello players

The same analyses, done for the violin players, were repeated for cello players. RMS maps from single differential sEMG signals were obtained from the same muscles, and ROAs over the MT, LT and ES muscles were identified. The MAI was obtained for each condition as discussed in section "E. Pre-processing setup". ICC values between the MAIs (over 10s of the recorded sEMG) were computed for the cello players and are depicted in Fig. 3b. Higher ICC values ($0.822 \leq ICC \leq 0.955$) were found for MT, LT, and LES muscles compared to the RES muscle ($0.604 \leq ICC \leq 0.837$) of the cello players. This observation suggests a higher day to day variability of the RES compared to the other muscles, in particular for strings 1 and 3.

Fig. 5 shows the MAI of MT and LT versus the string number and the bowing type for both student (solid line) and professional (dashed line) cello players in the first session of recording, without backrest support. An increasing trend in the MAI from string number 1 toward string number 4 was observed. The increasing/decreasing trend from bowing down (toward the tip) to bowing up (toward the tail) is opposite with respect to violin players. The peaks in the trapezius MAI were observed during the sliding phase of the bow from the tail toward the tip. The same pattern of activity observed in violinists can be clearly seen in both MT and LT of cello players (Fig. 5b).

Figure 5 about here

Fig.5 c-f show the MAI of the ES muscles while playing fast movements (detaché tail and detaché tip) for all cellists and Fig. 6 describes the effect of string, slow or fast movements, the presence of backrest on the activity of the MT, LT, RES, LES. If the CI does not include the zero point the difference is potentially significantly different from zero. Unlike what happens for violinists, data from detaché tail do not show a significant difference (as defined in section F of Methods) and asymmetry in the lumbar's muscle activities, possibly due to the less demanding position of the instrument. The MAI of the ES were significantly different during detaché tip among cellists when no backrest support was used (higher MAI at left, see Fig.6b where the CI is below the zero line). For the cello players, a statistically significant difference in the MAI between with and without backrest conditions was observed only for LES (Fig $6b_3$). We also observed a statistically significant difference in the MAI between RES and LES without backrest during detaché tip (Fig.6 b_4), and the difference between LES and RES disappeared with the use of the backrest support (Fig. 6 b_4). Panels in Fig 6 show that the two sessions of experiments were not significantly different for both violin (Fig $6a_1$-Fig $6a_5$) and cello players (Fig $6b_1$-$6b_5$) and usually the two CIs covers each other indicating the repeatability of the measurements in different days.

Figure 6 about here

DISCUSSION

Musicians are very susceptible to playing-related musculoskeletal disorder (PRMD) (Fjellman-Wiklund, Grip, 2004b, Zaza, 1998) likely related to muscle activity. The conventional bipolar technique to quantify EMG in musicians (Berque and Gray, 2002) provides a general idea of local muscle activity but is very sensitive to electrode location. In contrast, a grid of electrodes provides the EMG amplitude distribution above the muscle, and a region of high amplitude can be identified. Study of PRMD was not in the scope of this work but could be addressed in the future using the HDsEMG technique whose proof of concept is provided in this work. As proof of concept demonstrating the ability to extract meaningful information from the distribution of muscle activity in musicians, we analyzed the single differential (SD) sEMG maps of MT, LT, RES, LES in healthy violin and cello players. Since monopolar sEMG signals might be affected by unwanted electrical potential sources such as other muscles active during playing (cross-talk), we used more selective sEMG maps, from single differential (SD) signals (Fig. 2c), which attenuate non-propagating components of the electrical signal. As a representative value of muscle activity, MAI allows comparison between different playing techniques, speeds and posture for the same subject. In this work, the MAI is not normalized, and no comparison is made across subjects. Comparisons are made for different conditions (different strings, with/without backrest, etc) and the differences between conditions are discussed and presented in Fig. 6a for violin and 5b for cello players.

As evident from Fig 6, for both violin (Fig $6a_{1-5}$) and cello players (Fig $6b_{1-5}$), the 95% CI corresponding to the two sessions overlap almost completely and no significant difference was observed in the MAI values recorded in two different days thereby supporting the conclusion that the measurements are repeatable in a test-retest situation. Fig. 3 also supports the repeatability of the measurements. ICC values are considered a measure of agreement between the MAIs values across days, and our results demonstrate reliable surface EMG recordings on different days (Andersen et al. , 2014, Atkinson and Nevill, 1998). Our experimental condition was not fully isometric, so comparing the reported ICC values with the results reported by Anderson et al. (Andersen, Christensen, 2014) is questionable.

The MAI is a function of the string that is played. When playing the violin or cello, the player's bowing arm follows a certain trajectory that is largely dependent on the string being played. For each trajectory, muscles that span the shoulder, elbow and wrist joints should activate in a different spatio-temporal pattern. Therefore, it is expected to observe different MAI for different strings. Fig 6 a_1) and b_1) confirm the effect of the string played on the MAI of MT compared to the first string (the most medial string on with respect to the subject's body) during large bowing for violin and cello players respectively.

The spatial pattern of activity is different between bowing down and bowing up for both violin (Fig 2c, Fig 4 a-b; Fig 6a_2) and cello players (Fig 5 a-b; Fig 6b_2). In violin players, during bowing down, the MT was not as active as when performing bowing up (MAI mean difference 21.1μV_{rms} with a 95% CI from 17.3 to 25.0 μV_{rms}, Fig 6a_2).

The fibers of the MT arise from the spinous process of the seventh cervical, and the spinous processes of the first, second, and third thoracic vertebrae. They are inserted into the medial margin of the acromion, and into the superior lip of the posterior border of the spine of the scapula. This configuration allows the MT to retract the scapula (Kendall, 2005) resulting in a greater MAI value in the condition of bowing up with respect to bowing down in violin players (Fig 6a_2). On the other hand, the LT is mainly responsible for depressing the scapula (Kendall, 2005) and also contribute to the scapular upward rotation, which is required for raising the arm. Thus, the RMS map of activity obtained from the LT was expected to be less sensitive to bowing up and down compared to the MT (Fig. 6a_2 and 6b_2). The upper portion of the MT and the lower portions of LT appear to act together during bowing up (Fig. 2c) probably with the purpose of controlling the movement of the scapula. The LT likely acts eccentrically.

In cello players, the effect of gravity is less important because the player keeps the bow almost horizontal while playing. We could visually see the difference in holding the bow and playing the individual strings of violin and cello. We did not quantify the differences between cello and violin players although such differences can be seen qualitatively comparing Fig 6a with Fig. 6b. From a biomechanical perspective, there are distinct differences between violin and cello, the most notable of which is that the cello is played "upside down'" in comparison to the violin, so that shoulder elevation and flexion increases towards the upper register of the cello, while decreasing towards the upper register of the violin (Turner-Stokes and Reid, 1999). In cello players, the bowing "down" movement requires an abduction of the right arm obtained through the elevation of the elbow and depression of the scapula. It is expected to observe a greater MAI value for both MT and LT while abducting the bowing arm (bowing down) with respect to the bowing up where the arm moves back (adduction). We could qualitatively observe the difference in the motor control patterns for MT and LT between cello and violin players using the contrast analysis for the sEMG activities of the muscles during bowing up and down (Fig. $6a_{1\text{-}5}$, $6b_{1\text{-}5}$). The contrasts between bowing "up" and "down" for the MT and LT of the cello players showed a statistically significant difference (MAI mean differences -23.3µV_{rms} and -14.8 µV_{rms}, with a 95% CI from -30.1 to -16.4 µV_{rms} and from -21.7 to -7.9 µV_{rms} respectively, Fig. $6b_2$). The mentioned contrast was in the opposite direction with respect to the violin players, i.e. violin players contracted both MT and LT more during bowing up than bowing down while the cello players contracted the MT and LT more during bowing "down."

The contrast analysis between presence/absence of backrest support (Fig $6a_{3\text{-}5}$ and Fig $6b_{3\text{-}5}$) indicates that musicians may tend to lean or rotate their torso to some degree while playing the different strings. Leaning to one side changes the distribution or the activity level of erector spinae muscles in the two sides. For both violin (Fig $6a_3$) and cello (Fig $6b_3$), we observed that backrest support reduces lumbar muscle activity while playing. Specifically, in performing detaché tail (Fig $6a_5$) with violin, we observed higher activity (greater MAI) for the right ES muscle than the left ES.

The erector spinae muscles assist in the control of bending forward at the waist as well as in return to the erect position. During performing fast movements such as detaché tail (Fig. $6a_5$), violin players turn and bend to some degree toward their left. This movement, likely causes the asymmetry in the lumbar MAI values (the difference between the right and left MAI sample means is 5.7µV_{rms} with a 95% CI from 1.3 to 10.0 µV_{rms}, Fig. $6a_4$). In detaché tip (Fig $6a_4$) no leaning toward the left is needed since the length of the bow compensate the required length to reach the string with the tip of the bow. Contrariwise, in cello players, playing with the tip of the bow requires abduction of the arm, unbalancing the lumbar muscle activity (the difference between the right and left MAI sample means is -8.9µV_{rms} with a 95% CI from -16.5 to -1.2 µV_{rms}, Fig $6b_4$). Even assuming the same length and weight of the bow for both violin and cello, since the violin is placed more laterally to the player's sagittal plane comparing to cello, less effort for violin players is needed to slide the tip of their bow on the strings. Fig.$6b_4$ shows that during detaché tip, cello players have bigger MAI on their left side when they do not use backrest support (the CI between right and left ES is entirely below the zero line). Therefore, in long performances, leaning on a backrest support can reduce the activity of the cello player's back muscles.

A potential application of this analysis is in ergonomic studies and in designing or selecting a proper seat. The minimum difference between the MAI of the RES and LES was obtained when the cellists played with the tail of the bow (Fig. $6b_5$) and violinists played with the tip (Fig. $6a_4$). Symmetric activity on lumbar muscles can be observed in this case (Fig. $6a_4$, Fig. $6b_5$). We did not quantify the range of motion of the waist or the arm abduction that is required for detaché tip or tail. Kinematic data would allow the correlation between the biomechanics of the movements and the electrophysiological information for optimal seat design.

The level of experience in performing a task is a factor that requires comparisons between subjects as well as MAI normalization. Comparing the level of proficiency needs a higher number of subjects considering age, gender and anatomical differences, which is beyond the scope of this work.

In summary, we recorded the sEMG activity of the MT, LT and the LES, RES of professional and student cello and violin players. By the spatial average RMS value over the active region (identified by automatic image segmentation technique and defined as MAI) we found:

1. A two-fold increase in the trapezius (middle/lower) MAI from string 1 to string 4 for both violin and cello players.
2. A difference between bowing down and bowing up in the trapezius (middle/lower) MAI in violin players. In particular, sliding the bow from the tip toward the tail requires higher muscle activity (about 50% higher than sliding it from the tail toward the tip).
3. A difference between bowing down and bowing up in the trapezius (middle/lower) MAI in cello players. In particular, sliding the bow from the tail toward the tip requires higher activity (about 50% higher than sliding it from the tip toward the tail).
4. The presence of backrest support reduces the MAI of both left and right erector spinae muscles in both violin and cello players (about 20% lower).

5. Playing detaché tail causes higher activity of the RES compared to the LES for violin players to keep the player balanced. In performing detaché tip, the lumbar activities of the left and right side are balanced.
6. Playing detaché tip causes higher activity of the LES compared to the RES for cello players. In a detaché tail performance, the lumbar activities of the right and left side are balanced.
7. Thirty minutes of free play did not cause significant changes in the MAI for any of the assessed muscles. This activity looks more like a warm-up session, which does not significantly affect either the muscle activity or the signal quality.

The 2-D sEMG technique demonstrated to be sensitive enough to reliably detect the small changes reported in the figures. Future research will concern the application of the technique to arm and forearm muscles.

LIMITATIONS OF THE STUDY

Only electrophysiological measurements were made in this work with a limitation of 128 electrodes. The electrode grids did not cover the entire trapezius or the entire erector spinae. Larger and stretchable arrays should be developed for measuring the deltoid and the upper trapezius in the neck region.

We reported the differences between conditions (different strings, with/without back rest, etc.) for different subjects. No comparison was made between subject groups. For such comparisons, based on age/gender/instrument/experience, a much larger population is needed for drawing conclusive statistical interpretations. Furthermore, sEMG data for inter-subject comparison should be reported in a normalized form (to be defined) which is very difficult to implement especially for the trapezius and the erector spinae muscles. In particular, different portions of the trapezius produce mechanical forces in different directions making this task very challenging.

Conclusions

The first conclusion of this work is that the HDsEMG technique can be used to study musicians' muscles while playing.

The second conclusion is that HDsEMG signal quality and information content are not affected by 30 min of playing a demanding piece and are repeatable on different days.

The third conclusion is that it is possible to detect sEMG differences associated with a) playing different strings of violin and cello, b) presence/absence of backrest, c) different types of bowing movements.

The reliability of the technique and the results outlined in this work justify further work on a greater number of subjects as well as the design of acquisition systems covering greater areas and more muscles with a larger number of electrodes.

CONFLICT OF INTEREST

The authors have no personal or financial conflicts of interest related to the present work.

ACKNOWLEDGMENTS

The authors are grateful to Prof. A. Colombo (Conservatorio Antonio Vivaldi, Alessandria, Italy), Prof. C. Bertola and Prof. E. Groppo (Conservatorio Giuseppe Verdi, Torino, Italy), Drs. G. Camarota (Ergonomia-Prevenzione-Ambiente, EPA srl), M. Testone, C. Matassa (RAI), R. Bergamo, A. Mandrini (Varier srl) and the participating professors and students.

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FIGURE CAPTIONS

Figure 1: Each experimental session generates 48 recorded files each containing the signals from the four muscles of interest listed in Fig. 2. The recordings are obtained from 4 [strings] x 3 [bowing

types] x 2 [postures] x 2 [before/after exercise] conditions. The protocol was repeated on two different days. See the section “Measurement Protocol” for the bowing types and posture definitions. Totally, 16 violin players (13 students + 3 professionals) and 11 cello players (8 students + 3 professionals) participated in this study.

Figure 2: a) electrode grids (16x4 electrodes) placed on the medial side of the right trapezius muscle (caudal part of the UT, MT and LT, and above the RES and LES (two grids of 16x2 electrodes). For the trapezius, the rows of the grid are parallel to the spine of the scapula (i.e. approximately parallel to the muscle fibers of the UT and MT) and the columns are parallel to the spine. For the erector spinae muscle, the columns of the grids are parallel to the spine. b) two examples of the recorded signals from a representative subject (cello player during large bowing on the 4th string, without backrest support). Both monopolar and single differential (SD) signals are shown. c) example of SD RMS maps from the MT and LT muscle: Violin player, String 1, without backrest posture.
From each recorded file (see measurement protocol), SD RMS maps of activities (8x3 pixels) were prepared over 1s. Then, the region of activity (ROA) was found for each map, and Muscle Activity Index (MAI) was computed as the spatial average of the RMS values within the ROA. Bowing downs are t = 1, 3, 5, 7, 9 and ups are t = 2, 4, 6, 8, and 10. Please note different color scales (gray in printed version) for MT and LT.
UT = Upper Trapezius; MT = Middle Trapezius; LT = Lower Trapezius.

Figure 3: The intraclass correlation coefficient (ICC) as the measure of repeatability between the MAIs computed over 10s of the first sEMG recording session (day 1) and the MAIs of the second sEMG recording session (day 2). Data from 14 violinists and 9 cellists were used to compute the ICC values. ICC computation was based on the definition and the algorithm used by "R" software using the “irr” package (Gamer, Lemon, 2012).

Figure 4: Muscle Activity Index values (MAI; see text for definition) of each subject are shown versus the string number, separated into large bowing down and up of the first session without backrest support, for the middle (a) and the lower (b) trapezius muscle of both professional (dashed line) and student (solid line) violin players. c) and e) MAI of the left erector spinae (LES) during playing detaché tip and tail respectively. d) and f) MAI of the right erector spinae (RES) muscles during playing detaché tip and tail respectively. Only the data from detaché (tip/tail) movement are shown because these conditions require slightly different postures and produce different sEMG activities on the two sides.

Figure 5: Muscle Activity Index values (MAI; see text for definition) of each subject are shown versus the string number, separated into large bowing down and up of the first session without backrest support for the middle (a) and the lower (b) trapezius muscle of both professional (dashed line) and student (solid line) cello players. c) and e) MAI of the left erector spinae (LES) during playing detaché tip and tail respectively. d) and f) MAI of the right erector spinae (RES) muscles during playing detaché tip and tail respectively. Only the data from detaché (tip/tail) movement are shown because these conditions require slightly different postures and produce different sEMG activities on the two sides.

Figure 6: Summary of the statistical analysis obtained using the contrast theory and confidence intervals (CI) for violin (top panels) and cello (bottom panels) players' data. The ordinates of all panels (a_1-a_5, b_1-b_5) represent the mean and the 95% confidence interval of the difference between the values of the Muscle Activity Index (MAI, see the text for definition) corresponding to different conditions. Statistical significance is indicated by the fact that the bar for each condition does not cross the zero line (CI). a_1 and b_1): string effect on the MAI from the MT muscle for the violin and the cello players respectively; a_2 and b_2): effect of backrest on ES muscles of violin and cello players respectively; a_3 and b_3): large bowing effect (up/down) on trapezius muscles of violin and cello players respectively; a_4) and b_4): detaché tip effect on ES muscles of violin and cello players respectively; a_5 and b_5): detaché tail effect on ES muscles of violin and cello players respectively. Each panel is labeled with the MAI difference being tested against zero. For example, panel a_2) shows that the difference "MAI in bowing up minus MAI in bowing down" for the MT and LT is positive for violin players; panel b_2) shows that the same difference is negative for cello players. The dot depicts the mean, and the bars depict the 95% CI of each difference.
MT: middle trapezius muscle. LT: lower trapezius muscle. LES and RES: left and right erector spinae muscles.

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Table 1: Demographic data of participants in the study. For the professional players the values are reported and for the student players mean ± standard deviation.

Characteristics	Violin players		Cello players	
	Professionals	Students	Professional	Students
Number of participants	3	13	3	8
Age (years)	61, 42, 58	25 ± 14	52, 55, 62	26 ± 18
Experience (years)	48, 30, 45	11.3 ± 4	40, 46, 49	6.5 ± 2
Body mass (kg)	110, 75, 70	61.8 ± 15	95, 62, 88	54.4 ± 16
Height (cm)	180, 180, 170	167.3 ± 6	179, 176, 186	163.4 ± 13
BMI (kg/m^2)	33.2, 23.1,24.2	21.96 ± 4	29.7, 20.0, 25.4	19.9 ± 3
Gender (M-F)	3-0	5-8	3-0	3-5

Figure

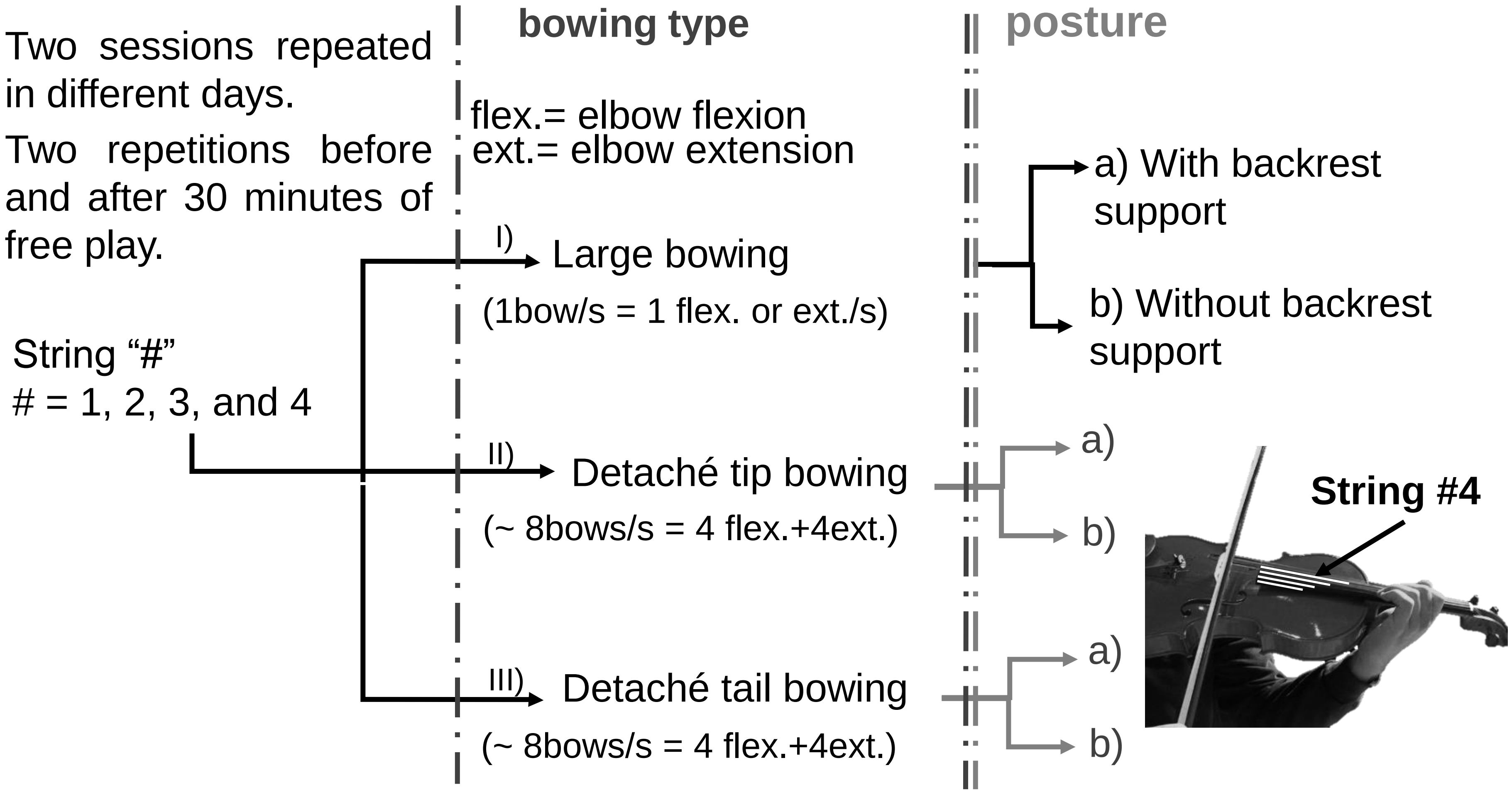
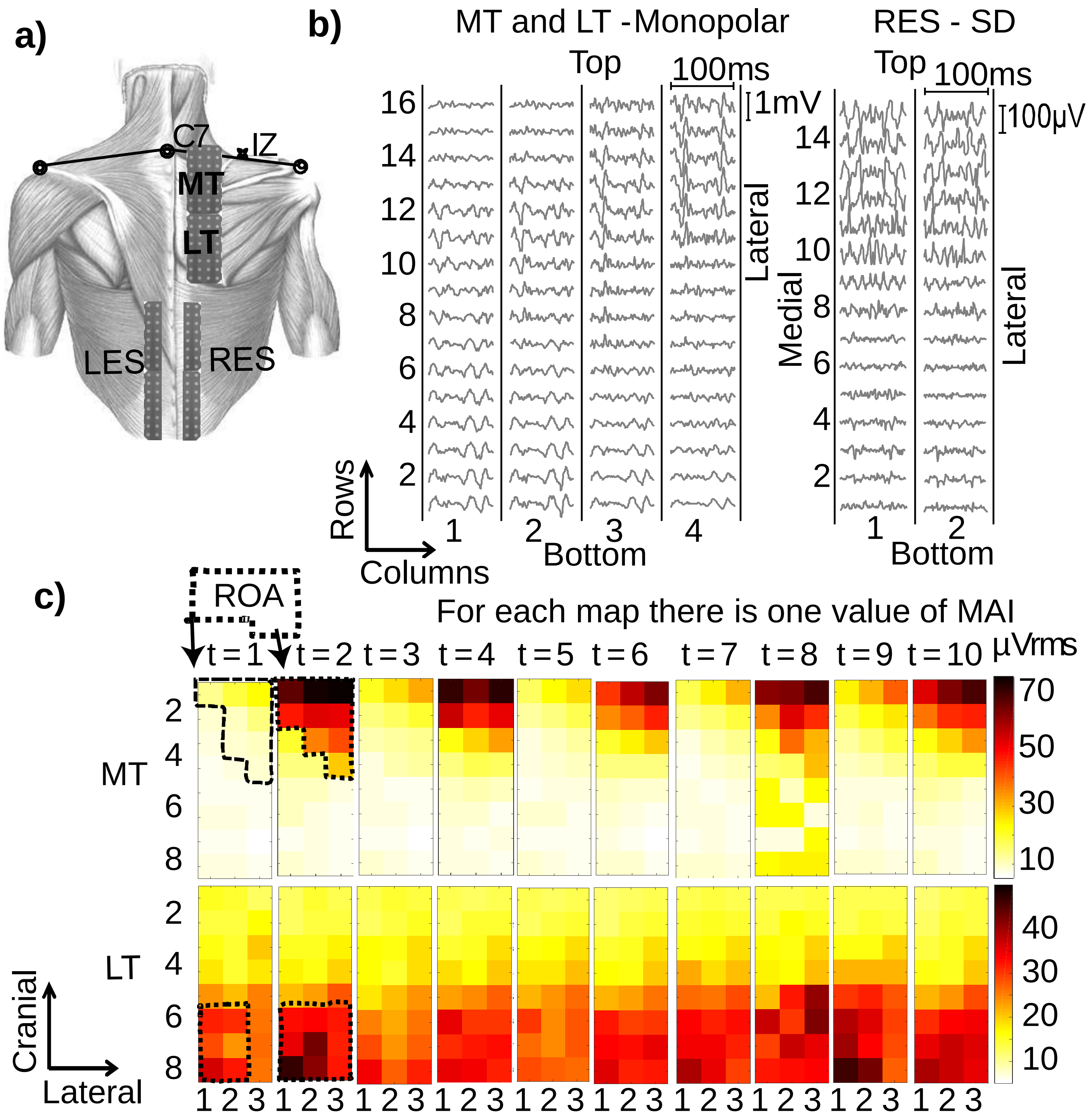

Two sessions repeated in different days.
Two repetitions before and after 30 minutes of free play.
String "#"
= 1, 2, 3, and 4
bowing type
flex.= elbow flexion
ext.= elbow extension
I) Large bowing
(1bow/s = 1 flex. or ext./s)
II) Detaché tip bowing
(~ 8bows/s = 4 flex.+4ext.)
III) Detaché tail bowing
(~ 8bows/s = 4 flex.+4ext.)
posture
a) With backrest support
b) Without backrest support
a)
b)
a)
b)
String #4

Fig.1



a)
C7
IZ
MT
LT
LES
RES
b)
MT and LT -Monopolar
RES - SD
Top
100ms
1mV
100µV
Lateral
Medial
Rows
Columns
Bottom
c)
ROA
For each map there is one value of MAI
t = 1
t = 2
t = 3
t = 4
t = 5
t = 6
t = 7
t = 8
t = 9
t = 10
µVrms
MT
LT
Cranial
Lateral

Fig.2

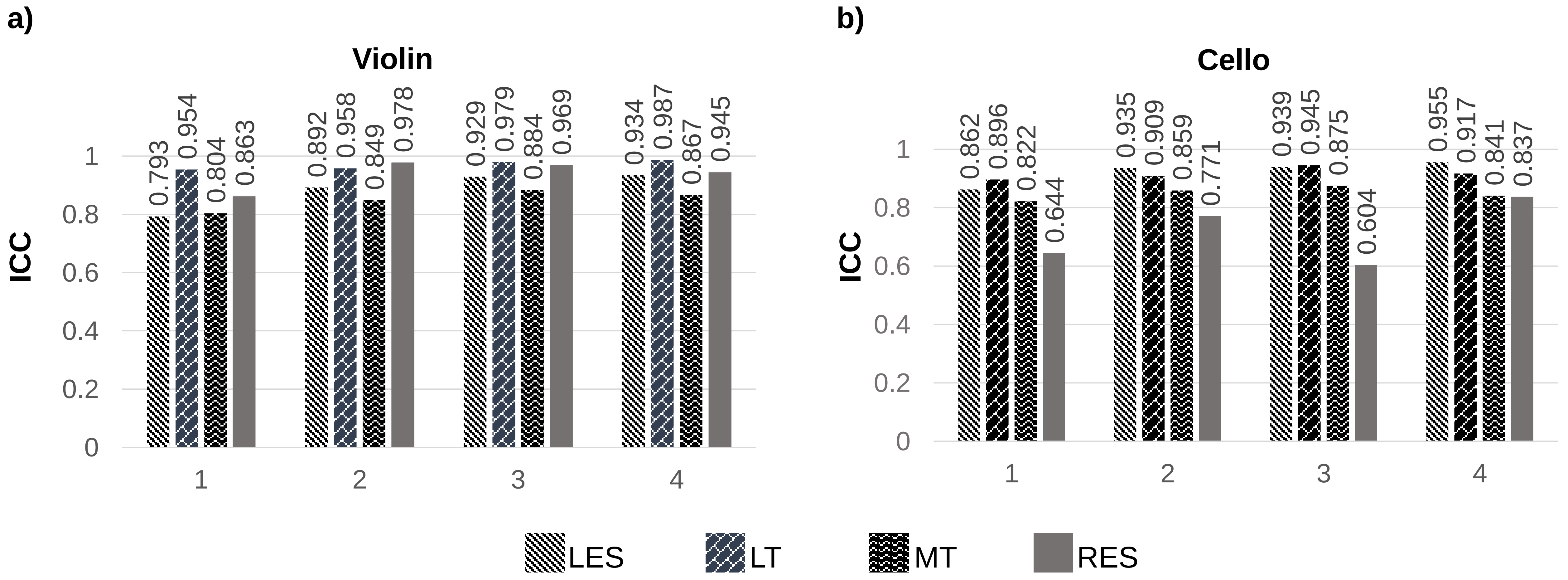

a)
Violin
ICC
1
0.8
0.6
0.4
0.2
0
0.793
0.954
0.804
0.863
0.892
0.958
0.849
0.978
0.929
0.979
0.884
0.969
0.934
0.987
0.867
0.945
1
2
3
4
b)
Cello
ICC
0.862
0.896
0.822
0.644
0.935
0.909
0.859
0.771
0.939
0.945
0.875
0.604
0.955
0.917
0.841
0.837
LES
LT
MT
RES

Fig.3

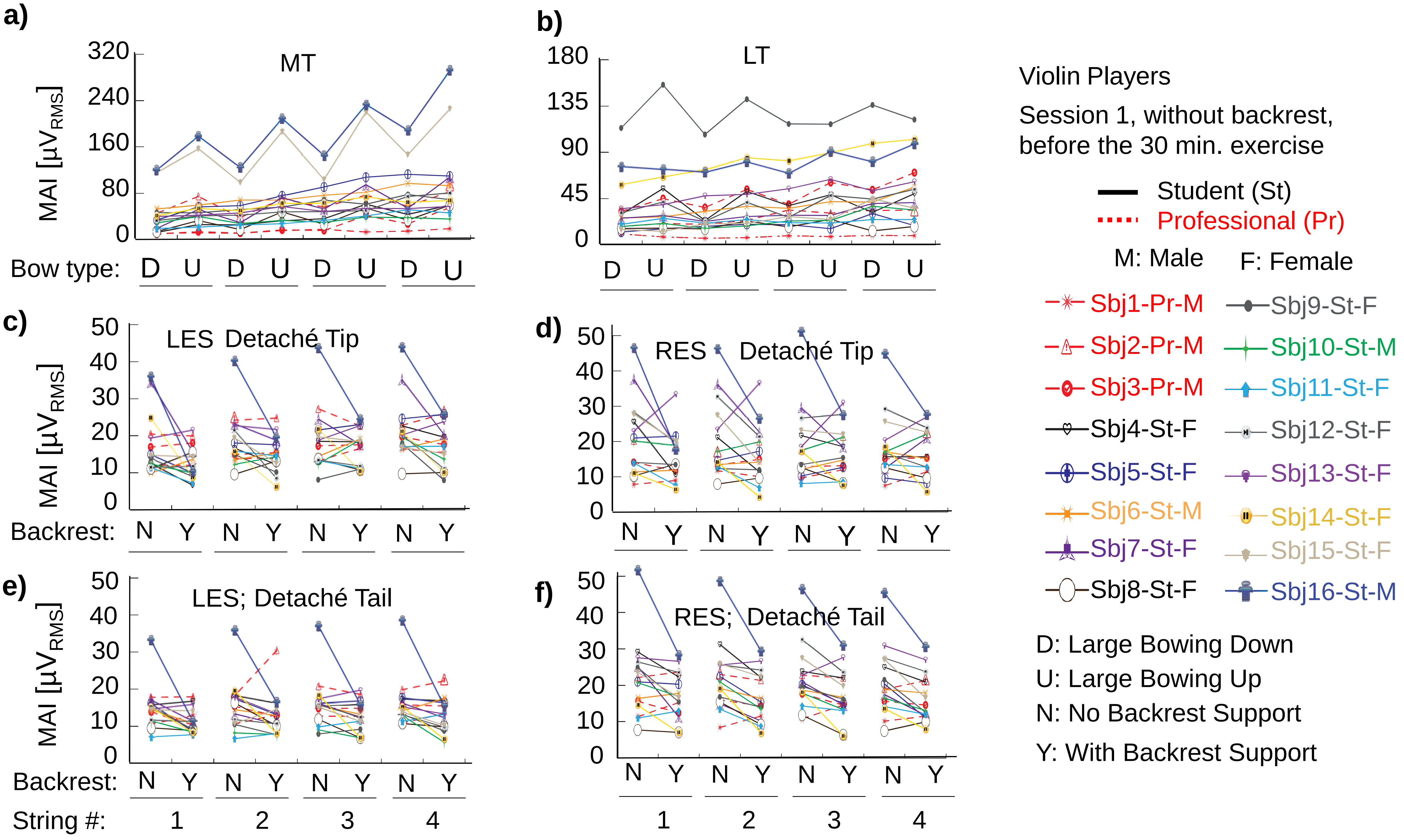

a)
MT
MAI [μV_RMS]
320
240
160
80
0
Bow type:
D U D U D U D U
b)
LT
180
135
90
45
0
D U D U D U D U
c)
LES Detaché Tip
MAI [μV_RMS]
50
40
30
20
10
0
Backrest:
N Y N Y N Y N Y
d)
RES Detaché Tip
50
40
30
20
10
0
N Y N Y N Y N Y
e)
LES; Detaché Tail
MAI [μV_RMS]
50
40
30
20
10
0
Backrest:
N Y N Y N Y N Y
String #:
1 2 3 4
f)
RES; Detaché Tail
50
40
30
20
10
0
N Y N Y N Y N Y
1 2 3 4
Violin Players
Session 1, without backrest, before the 30 min. exercise
Student (St)
Professional (Pr)
M: Male
F: Female
Sbj1-Pr-M
Sbj2-Pr-M
Sbj3-Pr-M
Sbj4-St-F
Sbj5-St-F
Sbj6-St-M
Sbj7-St-F
Sbj8-St-F
Sbj9-St-F
Sbj10-St-M
Sbj11-St-F
Sbj12-St-F
Sbj13-St-F
Sbj14-St-F
Sbj15-St-F
Sbj16-St-M
D: Large Bowing Down
U: Large Bowing Up
N: No Backrest Support
Y: With Backrest Support

Fig.4

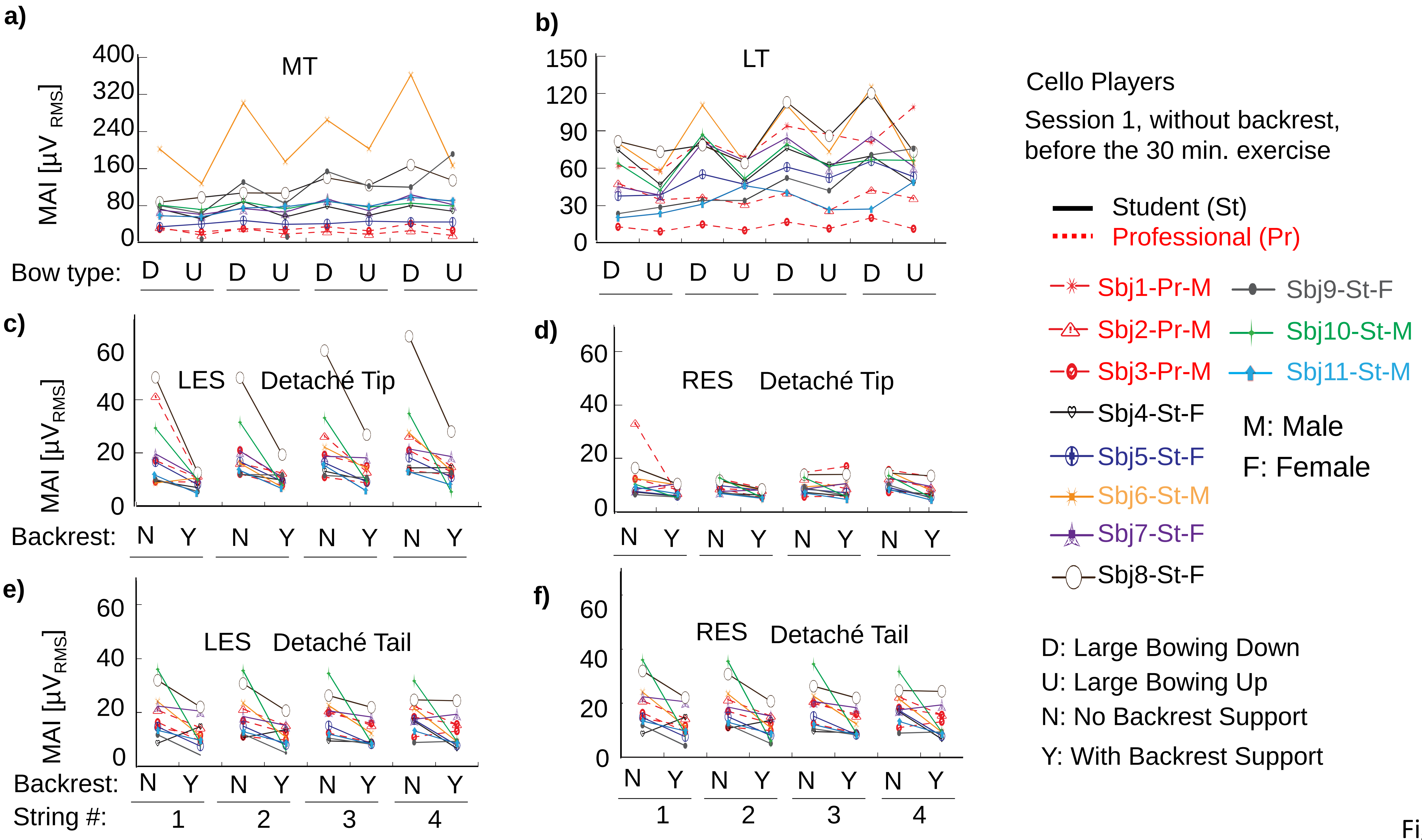

a)
MT
MAI [μV RMS]
400
320
240
160
80
0
Bow type:
D U D U D U D U
b)
LT
150
120
90
60
30
0
D U D U D U D U
Cello Players
Session 1, without backrest, before the 30 min. exercise
Student (St)
Professional (Pr)
Sbj1-Pr-M
Sbj2-Pr-M
Sbj3-Pr-M
Sbj4-St-F
Sbj5-St-F
Sbj6-St-M
Sbj7-St-F
Sbj8-St-F
Sbj9-St-F
Sbj10-St-M
Sbj11-St-M
M: Male
F: Female
c)
LES Detaché Tip
MAI [μVRMS]
60
40
20
0
Backrest:
N Y N Y N Y N Y
d)
RES Detaché Tip
60
40
20
0
N Y N Y N Y N Y
e)
LES Detaché Tail
MAI [μVRMS]
60
40
20
0
Backrest:
N Y N Y N Y N Y
String #:
1 2 3 4
f)
RES Detaché Tail
60
40
20
0
N Y N Y N Y N Y
1 2 3 4
D: Large Bowing Down
U: Large Bowing Up
N: No Backrest Support
Y: With Backrest Support

Fig. 5

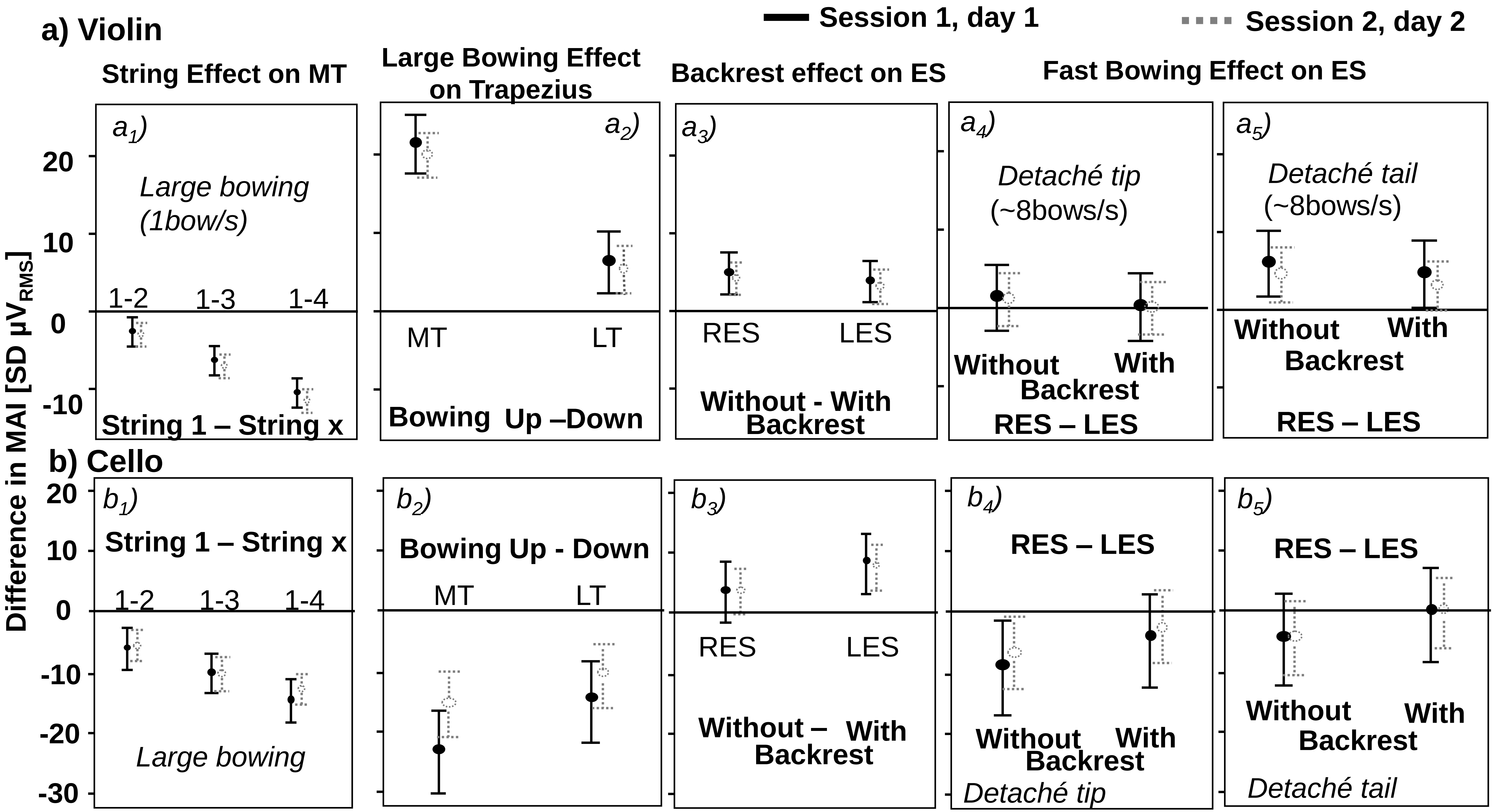

a) Violin
Session 1, day 1
Session 2, day 2
String Effect on MT
Large Bowing Effect on Trapezius
Backrest effect on ES
Fast Bowing Effect on ES
a1)
Large bowing (1bow/s)
1-2
1-3
1-4
String 1 – String x
a2)
MT
LT
Bowing Up –Down
a3)
RES
LES
Without - With Backrest
a4)
Detaché tip (~8bows/s)
Without
With
Backrest
RES – LES
a5)
Detaché tail (~8bows/s)
Without
With
Backrest
RES – LES
b) Cello
b1)
String 1 – String x
1-2
1-3
1-4
Large bowing
b2)
Bowing Up - Down
MT
LT
b3)
RES
LES
Without – With
Backrest
b4)
RES – LES
Without
With
Backrest
Detaché tip
b5)
RES – LES
Without
With
Backrest
Detaché tail
Difference in MAI [SD μV_RMS]
20
10
0
-10
-20
-30

Fig.6

Authors Biography

1. Babak Afsharipour

Babak Afsharipour graduated in Electronic Engineering at Azad University (IAUK, Iran) in 1997. He received his Master of Science in Biomedical Engineering at Tarbiat Modares University (TMU, Iran) in 2004. In 2011, Babak joined the Laboratory for Engineering of the Neuromuscular System (LISiN), and he obtained his Ph.D. in Biomedical Engineering at Politecnico di Torino (Torino, Italy) in 2014. Since 2015, he is a postdoctoral researcher at Department of Physical Medicine and Rehabilitation of Northwestern University (Chicago, USA) and a member of the Single Motor Unit (SMU) Lab at the Rehabilitation Institute of Chicago (RIC).

2. Francesco Petracca

Born in Turin (Italy) in 1989, in 2008 he got his degree from the Scientific High School G. Bruno of Turin, and in October 2013 he graduated in Biomedical Engineering at Politecnico di Torino with an experimental thesis titled: "Metallic Nanostructures for SERS applications synthesized with ink-jet printing technique.

2013 to 2015, he joined the Laboratory for Engineering of the Neuromuscular System (LISiN). His research also involves the study and the interpretation of EMG signals simulated by mathematical models.

3. Mauro Gasparini

Mauro Gasparini, Professor of Statistics at Politecnico di Torino since 2002, Ph.D. from the University of Michigan in 1992. Formerly Assistant Professor at Purdue University then Senior Statistician in Novartis, Basel, Switzerland.

Consultant with several pharmaceutical industries (Novartis, Alcon, Bayer, ABC Farmaceutici) and biomedical research centers (Molinette Hospital Turin, San Raffaele Milan, Istituto Tumori Toscano, Fondazione Edo Tempia Biella).

4. Roberto Merletti

Roberto Merletti graduated in Electronics Engineering from Politecnico di Torino, Italy, and obtained his M.Sc. and Ph.D. in Biomedical Engineering from the Ohio State University. He has been Associate Professor of Biomedical Engineering at Boston University where he was also Research Associate at the NeuroMuscular Research Center.

He has been Full Professor of Biomedical Engineering at Politecnico di Torino where he established, in 1996, the Laboratory for Engineering of the Neuromuscular System (LISiN) of which he has been director until Nov. 2015. He is Senior Member of IEEE, Fellow of ISEK, and a member of the Editorial Board of three international journals. He is author/editor of four textbooks on surface EMG.