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Analysis of High Density Surface EMG and finger pressure in the left forearm of violin players.

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Abstract

In the current study, wrist and finger flexor muscles of the left hand were evaluated using High Density surface EMG (HDsEMG) technology for 17 violin players. Additionally, pressure sensors were mounted below the second string of the violin in order to evaluate, simultaneously with HDsEMG, the finger pressure. Electrode grid size was 110x70 mm (12x8 electrodes with interelectrode distance IED=10mm and Ø=3mm). The objective of the study was to observe the activation patterns of these muscles while sequentially playing four notes SI(B), DO#(C#), RE(D), MI(E), at 2 bows/s (one bow up in 0.5 s and one down in 0.5 s) and 4 bows/s on second string; while producing a constant (CONST) or a ramp (RAMP) sound volume. HDsEMG images, obtained while playing the notes, were compared with those obtained during isometric radial or ulnar flexion of the wrist or of the fingers. Two image descriptors provided information on image differences.
Result showed that: a) the technique is reliable and provides reliable signals, b) recognizably different sEMG images could be associated to the four notes tested, despite the variability within and between subjects playing the same note, c) sEMG activity of the left hand muscles and the pressure on the string in the RAMP task were strongly affected in some individuals by the volume of the sound (controlled by the right hand), and much less in other individuals.
These findings pose the question of whether there is an individual or a general optimal way of pressing the violin strings with the left hand. The answer to this question might substantially modify the way of teaching string instruments.

Keywords: sEMG, musicians, violin, forearm muscles, playing related disorders

1. INTRODUCTION

1.1 General concepts about sEMG and HDsEMG

Surface electromyography (sEMG) studies the electric signals present on the skin surface above a muscle (or group of muscles) and generated by the action potentials propagating along the fibers constituting the motor units of such muscle(s). The instantaneous (time-varying) distribution of electric signals on this surface is referred to as analog sEMG-image or analog sEMG-map. Although the intensity and other properties of this time-varying image depend on the thickness and electrical properties of the subcutaneous tissue and many other factors[1], the sEMG images contain a great deal of information about underlying muscle activity and its control mechanisms.

Images of electrical potential are sampled in space by a set of surface electrodes. In the monopolar detection modality, each electrode detects the potential in one location with respect to a reference electrode placed away from the muscle(s) in question. In the bipolar or single differential (SD) detection modality the sEMG signal is detected as the potential difference between two adjacent electrodes. The traditional detection technique, adopted in most past works, was based on *only two electrodes* placed on the muscle(s) of interest. This very simple technique has many drawbacks extensively described[2,3] and provides limited and often misleading information.

In the past 20 years two dimensional (2-D) or “sEMG-imaging” detection techniques have been developed and described[2]. These techniques are also referred to as High Density surface EMG (HDsEMG). A rectangular grid of N rows by M columns of small electrodes (Ø= 1-5 mm, with center-to-center spacing of 5-10 mm) samples the analog image providing a set of NxM monopolar time-varying signals, each corresponding to one of the NxM pixels (electrodes) of the image. These signals are sampled in time (usually at 1000-2000 samples/s) and the amplitudes (and many other features) of these sampled NxM signals are calculated, over a given time period or “epoch” (typically 1 s), as the root of the mean square value (RMS) of the time samples. In this way, a new sequence of images is obtained (one per epoch) and referred to as the RMS-images or maps. If the NxM RMS values of each image are averaged, one average RMS value is obtained for each epoch. In addition the RMS-images may be processed to obtain other features such as the image centroid or a region of activity (ROA) that is the sub-image whose pixels show RMS values above a given threshold. RMS-images can then be investigated and compared using a variety of image processing techniques (see Methods).

1.2 Applications to violin players

Violin players perform daily intensive repetitive tasks and may suffer from Playing-Related Musculoskeletal Disorders (PRMDs) after some years[4]. Muscles of the back, shoulder, arm and forearm are involved. These muscles have been studied in many previous works[5,6,7,8,9] using the traditional bipolar detection technique and, more recently, using electrode arrays[10].

In particular Morasky et al.[11] stated that “Music instructors generally agree that unnecessary muscle tension not only leads to physical problems but also can interfere with performance quality”. LeVine et al.[12] stated that “EMG biofeedback was found to be an effective pedagogical tool for removing unwanted left-hand tension in nine violin and viola players”. More recently, Kelleher et al.[13] analyzed 34 articles (16 of which using sEMG techniques) and concluded that “There are few studies that investigate protective strategies, although it is expected that the field will progress to incorporate this type of research”. The development of such protective strategies requires a much deeper understanding of how muscles are (or should be) used in violin playing.

1.3 Objectives of the study and research questions.

This is a semi-quantitative feasibility study. The flexors of the left wrist and fingers have been investigated in this work using the HDsEMG technique in controlled conditions (see Methods) with the purpose of answering the following research questions:

1) how are the left wrist and finger flexors activated in controlled conditions of constant and increasing sound volume while playing single notes?
2) is the activation pattern repeatable within and between subjects?
3) how is such pattern related to the note played?
4) how is the pressure of fingers on a string related to the produced sEMG and sound?

This study reports only findings concerning the flexor muscles. Findings concerning both extensors and flexors will be reported elsewhere.

2. METHODS

2.1 Subjects

The wrist and finger flexor muscles of 17 violin players were investigated in controlled conditions. All musicians signed the informed consent form prepared for these tests. All the procedures used in this study were applied in accordance with the Helsinki Declaration of 1975, as revised in 2000 and

2008. The subjects were volunteer musicians recruited by means of a) a presentation of the project in their schools and b) notices posted in two "Conservatori musicali --" (Italy).

Although some musicians reported PRMD (see below) they were otherwise healthy students (11) and professors (6). Subjects affected by major pain or health problems were not included. Thirteen subjects out of 17 referred some degree of pain in the upper extremities, neck and back during or after playing. The pain level was evaluated using the Numerical Rating Scale[14] (NRS, 0= no pain, 10= intense pain) and reported in Table 1 with the other subjects' characteristics. All musicians used the same sensorized violin and played in sitting position.

The subject population is heterogeneous in terms of gender, age, career, hours of training per week (Table 1).

2.2 Tasks

The subjects were asked to play the four notes SI (B), DO# (C#), RE (D), MI (E) at 2 bows/s (one bow up in 0.5 s and one down in 0.5 s) and 4 bows/s, following a metronome at 60 bpm, for 10 s, on the second string (LA, A). The swing of the bow was chosen by each subject and was approximately 15-20 cm in the central portion of the bow.

First, each note was played at a constant volume (CONST) and then at increasing volume (RAMP1). The volume level was controlled by tracking a target indicated on-line on a computer screen. One finger at a time pressed the cord and the force applied to it was measured with the Force Sensing Linear Potentiometer (see 2.3). The RAMP test was repeated after 5 min of demanding free playing exercises (RAMP2) to test the stability of the electrode contacts and the intra-subject repeatability of the sEMG and force measurements. For each of the 24 tasks (CONST, RAMP1, RAMP2, four notes, two bowing speeds), 10 RMS-images were computed (one per second) as well as a global RMS-image computed over 10 s.

Table 1. Characteristics of the 17 violin players involved in the study.
NRS: Numerical Rating Scale[14]

Subject number	Student/ Professor	Male/ Female	Age (years)	Height (cm)	Body mass (kg)	Musical career (years)	Training (h/week)	Comments and remarks
1	P	M	58	183	110	50	20	No remarks
2	S	F	18	156	56	10	14	Low back pain during stand up playing (NRS=3)
3	S	M	19	186	73	8	8	Occasional pain in the right shoulder (NRS=5). Low back pain after a lot of playing hours (NRS= 7)
4	P	F	53	160	56	40	12	Continuous pain in the left neck region. (NRS=4)
5	S	M	20	164	52	8	14	Rigth lumbar pain after 1-2 hours (NRS= 5).
6	P	F	22	165	53	10	50	Upper back pain after 3 hours (NRS= 3)
7	S	F	18	155	49	11	5	No remarks
8	S	F	16	162	80	9	4	Left forearm pain and back pain after half hour. (NRS=2).
9	S	F	21	160	50	10	21	Viola player. General pain in upper extremity, shoulders and neck (NRS: not available)
10	S	M	25	170	52	13	30	Viola player. Left shoulder and upper back pain after 4 hours of playing. (NRS 6).
11	S	F	19	163	53	12	3	Viola player. Left arm and chest pain after 1 day of playing (NRS 4).
12	P	F	53	150	55	44	10	No remarks
13	S	F	24	168	55	18	30	Shoulder and back pain after 1 hour of playing. (NRS 5)
14	P	F	28	165	53	7	25	Lumbar pain in the evening (NRS=5).
15	S	F	19	157	50	13	20	Right hand and shoulder pain (NRS= 6)
16	S	M	17	190	60	11	10	Left hand pain after training (NRS= 7)
17	P	F	42	165	60	30	3	No remarks
Statistics (mean and range values)								
N	S/P	M/F	Age (years)	Height (cm)	Body mass (kg)	Musical career (years)	Training (h/week)	Thirteen subjects are affected by Playing Related Disorders (back, shoulder or arm pain of various degree).
17	11/6	12/5	28 16-58	166 150-190	60 49-110	18 7-50	16 3-50	

2.3. Force and sound acquisition and processing.

The violin was sensorized by placing a Force Sensing Linear Potentiometer (FSLP, Interlink Electronics, mod 34-00022) under the second string (LA, A)[15,16]. The output signal was sampled at 40 samples/s. A clip microphone was placed on the bridge of the violin and its signal was sampled at 8000 samples/s. Both signals were converted with a 10 bit A/D converter and stored in separate files.

2.4 Surface EMG signal acquisition and conditioning.

A grid of 96 (12x8) silver electrodes (Ø= 3 mm, center to center interelectrode distance = 10 mm), designed at LISiN, Politecnico di Torino, was placed on the region covering the wrist and finger flexor muscles, as indicated in Fig 1. The electrode grid was fixed with 1 mm thick perforated double adhesive foam layer with holes filled with conductive paste (Ten20, Weaver and Company) corresponding to the electrodes. The skin under the electrodes was previously rubbed with an abrasive paste (Nuprep, Weaver and Company) and rinsed with a wet cloth to improve the electrode contact and signal quality.

All monopolar signals detected from each electrode (pixel) were amplified and bandpass filtered (10-750 Hz) before sampling at 2048 samples/s and were then A/D converted at 12 bits (Amplifier model USB128 by OT Bioelettronica, Torino). Digital bandpass filtering between 20 and 400 Hz with a 2nd order Butterworth bidirectional filter was then applied to the raw signal.
The first 10 harmonics of the power line were removed and replaced by spectral interpolation[17]. This procedures implies computing the Fourier transform of the signal (epoch = 1s, freq. resolution = 1 Hz) and replacing the harmonics at 48 to 52 Hz, 98-102 Hz, etc. (up to 500 Hz) with the value resulting from interpolation of the previous and following two harmonics. Inverse Fourier transform then provides a signal with reduced power line interference (Software developed at LISiN using Matlab 7).

2.5 Surface EMG image processing and comparison

Surface EMG amplitude values (such a RMS-images) cannot be compared among subjects because they depend not only on the level of muscle activation but also on a number of confounding individual factors[1]. They can only be compared, across different tasks, within each subject.
To provide means for at least topographical comparisons among tasks the procedure described below in 2.5.1. was adopted. RMS-images were computed for monopolar signals over the entire 10-s epoch, over 10 1-s epochs (one bow-down and one bow-up) and on epochs of about 0.5 s

corresponding alternatively to one bow-down and one bow-up. The sound signal was used to separate up-swings from the down-swings of the bow.

2.5.1 Image comparison using the distance between topographical patterns

Before the test (described in section 2.2) the wrist and hand of each subject were locked into an isometric brace and each subject was asked, and trained for a few times, to produce, at his/her best, maximal voluntary contractions (MVC) of the flexor carpi ulnaris, of the flexor carpi radialis, and of index, middle, ring and little finger flexor muscles, under the supervision of a physical therapist. Each MVC force value was recorded and the procedure was repeated by asking each subject to perform again each contraction at 20% MVC level by matching a target set on a computer screen. The 20% MVC value is not critical and was chosen arbitrarily for providing reference regions of sEMG images at low activation levels. The monopolar RMS-images were acquired in these conditions, over a 10-s epoch, and used as reference images as indicated below.

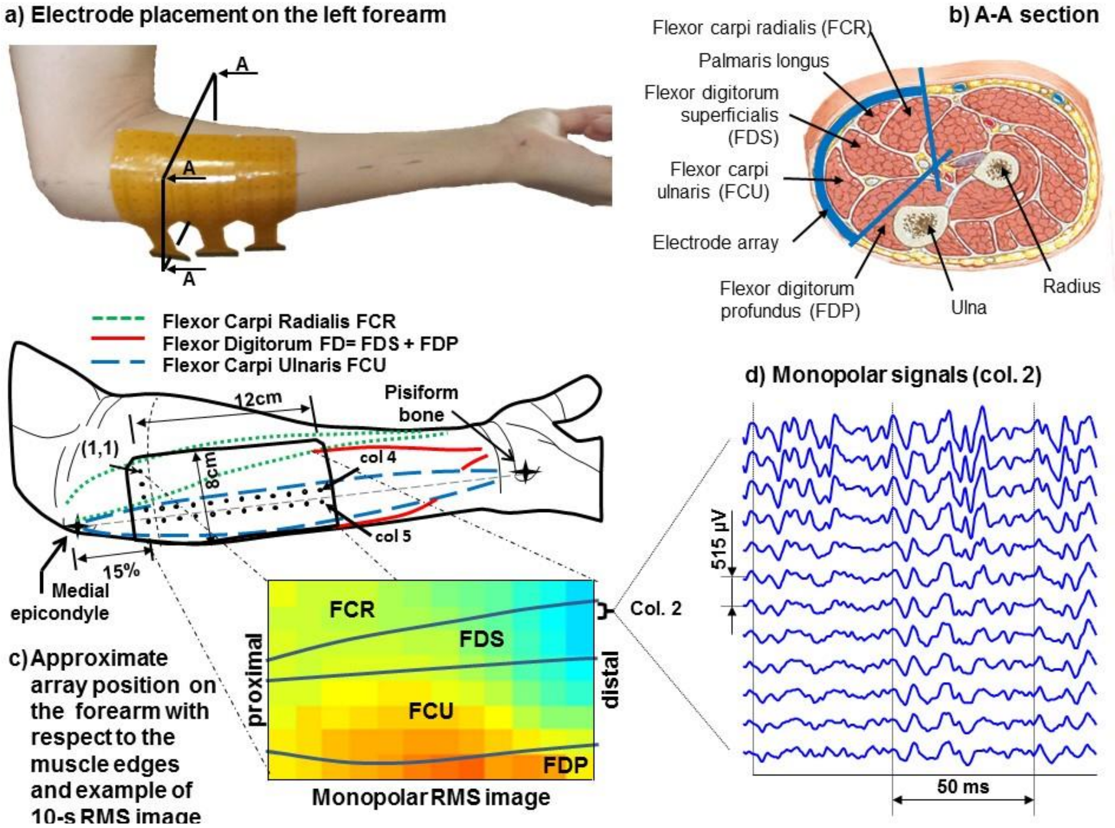


Fig. 1. a) Placement of the electrode grid over the wrist and finger flexor muscles. b) Cross-section of the forearm at level A-A and position of the grid. The palmaris longus is aggregated to the flexor carpi radialis. This muscle is absent in 16% of the population[18]. c) drawing of the forearm and of the electrode grid and underlying muscles. The line connecting the pisiform bone to the medial epicondyle is between col 4 and 5 of the grid. The first row is at 15% of the distance between the pisiform bone to the medial epicondyle. The color map shows an example of monopolar RMS-image over 10 s. d) example of monopolar sEMG signals from col. 2 of the array.

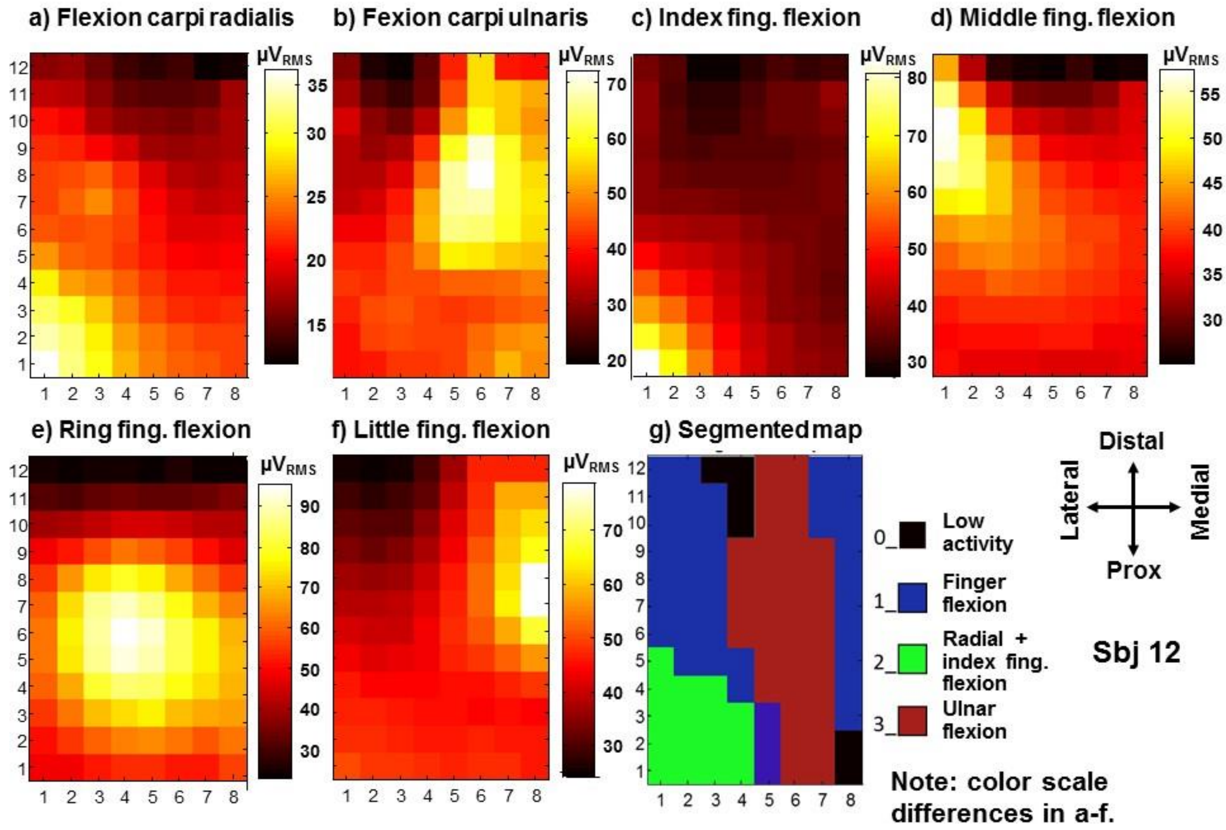


Fig. 2a-f. Reference RMS-images obtained from subject 12 while performing, after some training, isometric contractions at 20% of the maximal voluntary contraction (20% MVC) involving the indicated muscles. Regions of high activity do not necessarily indicate specific muscles but regions activated by a specific effort. g) outline of the template indicating the regions of high sEMG corresponding to the indicated efforts. Note different scales in a-f. See text for details.

Six reference RMS-images of one subject (n. 12) are depicted in Fig. 2 a-f. For each of these RMS-images a ROA was defined as that including the pixels with amplitude above 70% of the maximum. This threshold was chosen arbitrarily. From the resulting six binary images a new image was created (by visual inspection) as depicted in Fig. 2g. In this reference image three ROAs were identified and labeled as “radial and index finger flexion” (the two regions overlapped), “ulnar flexion” and “finger flexion”, which included the ROAs of the middle, ring and little finger. Pixels belonging to more than one area were associated to the area corresponding to either radial or ulnar flexion because of their larger anatomical representation (Fig. 1b).

A few pixels showing low activity in all conditions were also identified and marked. Fig. 2g, therefore, provides a template of rough topological distribution of sEMG amplitude corresponding to patterns associated to three main tasks in isometric conditions and low contraction levels of each subject. No amplitude information is contained in the image of Fig. 2g. The reference images obtained from the 17 subjects are depicted in Fig. 3 and appear to be similar across subjects with the exception of subject 1 and 6.

A threshold equal to 70% of the maximum RMS value of each image was also applied to the RMS-images obtained during the execution of the tasks described in 2.2 (playing four notes on the second string). In this way ROAs were defined on the forearm and a new binary image (pixels below/above 70% of RMS_{max}) was created, for each task and each subject, over the 10-s epoch.

This ROA image was overlapped with the reference image previously obtained, for the same subject, during the isometric reference contractions. The fraction of pixels of the ROA overlapping region 1, region 2 and region 3 of the reference image depicted in Fig. 2g were recorded and provided a three bar histogram (one bar per region) that allowed a) a topographical assessment of the activation of the three muscle regions and b) the comparison between two images. The heights of the bars were expressed as percentages of pixels of the ROA overlapping region 1, region 2 and region 3 of the reference image (Fig. 2g).

A topographical comparison between two RMS-images having ROA1 and ROA2 was implemented using a repeatability index (R_{Ind}) defined as the Euclidean distance between two points in 3D space whose coordinates x_1, y_1, z_1 and x_2, y_2, z_2 are the heights of the three bars of the two histograms defined above. These heights are expressed as the percentage of pixels of ROA1 belonging to the three regions of the reference image (Fig. 2g) and the percentage of pixels of ROA2 belonging to the three regions of the same reference image. This distance is defined in eq. 1.

$$R_{ind} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \qquad (1)$$

Other image descriptors could be adopted as reported by Gallina et al.[19] who compared the coordinates of the centroid (or barycenter) of two images. In our context the histogram method is more appropriate because very different images may have the same centroid.

The average of RMS in space, over the pixels of each image, was also computed over each 1-s epoch, for the 10 s playing, providing a trend of RMS versus time.

2.5.2 Image comparison using the mean square differences between normalized sEMG images.

A second index used for comparison of two RMS-images is based on the Mean of the Square Differences (*MSD*) between the corresponding pixels of the two images, each normalized with respect to the RMS-image peak value. This index is defined in eq. 2 where RMS'_A and RMS'_B are the values of RMS-images A and B (one value per pixel) normalized with respect to their respective maximum, and R and C are the number of rows and columns of the two images.

$$MSD = \frac{\sum_{r=1}^{R}\sum_{c=1}^{C}\left[RMS'_A(r,c) - RMS'_B(r,c)\right]^2}{RC} \qquad (2)$$

MSD ranges from 0 (identical images) to 1 (either complementary checkerboard images or one image of zeros and one image of ones). However, random selection of RMS'_A and RMS'_B values from a uniform distribution in the range 0-1 produces a *MSD* value of 0.17 ± 0.02 (N=1000 repetitions of the generation process). It seems therefore more reasonable to consider this value, corresponding to random differences between two maps, as a reference and normalize the *MSD* with respect to 0.17 (defined as 100% difference) rather than with respect to 1.

The differences between the sEMG spatial distributions associated to the four notes were evaluated using the *MSD* (eq. 2) between RMS-Images. For each subject the *MSD* were computed in two ways:

1) between the RMS-images of the same note played in different conditions, and
2) between the RMS-images obtained in the same condition (bow velocity, sound volume, before or after exercise) when different notes are played.

In the first case, *MSD* was computed comparing RMS-images of SI vs SI, DO vs DO, RE vs RE, MI vs MI, played in all tasks: a) different velocity (2 and 4 bows/s), b) different sound volumes (CONST and RAMP) and c) before and after fatigue (RAMP1 and RAMP2). For each subject and each note 15 *MSD* values were obtained. These indices outline the differences between sEMG spatial distributions that can be attributed to the different conditions when the same note is played.
In case 2, every note was compared with the remaining three (SI vs All, DO vs All, RE vs All, MI vs All) played in the same condition (i.e., CONST volume at 2 bow/s, CONST volume at 4 bow/s, etc.). In this second case 18 *MSD* values were obtained for each subject and each note. These indices outline the differences between the sEMG spatial distribution introduced by the notes and by the playing condition.

2.6. Surface EMG, force and sound during bow up and bow down.

The force and sound signals were plotted versus time and each plot was divided into epochs of about 0.5 s each, corresponding to swings- up and to swings- down of the bow, identified from the sound plot. RMS-images were produced over the corresponding epochs, in synchrony with force and sound signals. This procedure allowed the analysis of sEMG activity of the left wrist and finger flexors during the bow-up and bow-down actions of the right arm.

During the 10 s of CONST volume and the 10 s of RAMP1 volume the force pressing the second string was recorded together with the RMS-images of sEMG of the left wrist and finger flexors. Mean force and average value of each RMS image were computed over ten 1 s epochs, providing 10 values that were plotted versus time. The regression coefficient (slope) of a linear regression of each of these two variables versus time was computed. The procedure was repeated for the RAMP task.

2.7 Measurement on two separate days

For a few subjects it was possible to repeat the test (section 2.2) on two days. Electrode grids were re-positioned by means of skin- marks (Figure 1). The reference images were those of the first day. For these subjects the MSD index (eq. 2) was computed between each condition of the two days.

2.8 Statistical analysis

A one way repeated measures ANOVA within each subject (equivalent to a t-test) was adopted to compare, in a paired way, the features of interest (e.g., sEMG index between CONST and RAMP condition). A multiple linear regression model was not adopted in this work due to the limited number of subjects with respect to the number of factors (e.g., note, bow velocity, sound volume).

3. RESULTS

3.1. Reference maps

Fig. 3 shows the reference maps obtained for the 17 subjects as described in 2.5.1 (Fig. 2g corresponds to subject 12). It is evident that the isometric contractions at 20% MVC (radial + index flexion, finger flexion, ulnar flexion) produce similar activation patterns across subjects, with occasional differences (such as in subjects 1 and 6). Therefore the reference maps used for generating the histograms described in 2.5.1 are rather similar across subjects indicating that all subjects produce high sEMG signals in the same regions when flexing wrist (in the radial or ulnar direction) and fingers at 20%MVC in controlled conditions. It is therefore reasonable to consider these maps as valid individual references for identification of patterns and for performing topographical comparisons within subjects.

3.2. Repeatability

3.2.1. Time course of sEMG RMS in RAMP tasks

As indicated in 2.2 (Tasks) the RAMP1 test was repeated after 5 min of demanding free playing exercise (RAMP2). In all cases the signal quality was good (visual observation), indicating a) electrode stability and, b) the fact that any observed difference is not due to alterations of the detection system but can be associated to different sEMG patterns. The regression of force and RMS (spatial average of each of the 10 RMS-images computed over 1 s each) versus time showed no significant difference (see section 2.8) between slopes (RAMP1 with respect to RAMP2) for each note and each bow velocity.

This observation indicates that the spatially averaged RMS values of the ten 1-s RMS-images have similar time courses in RAMP1 and RAMP2; however this similarity of RMS values does not imply similar RMS-images. This issue is further discussed below in section 3.5.

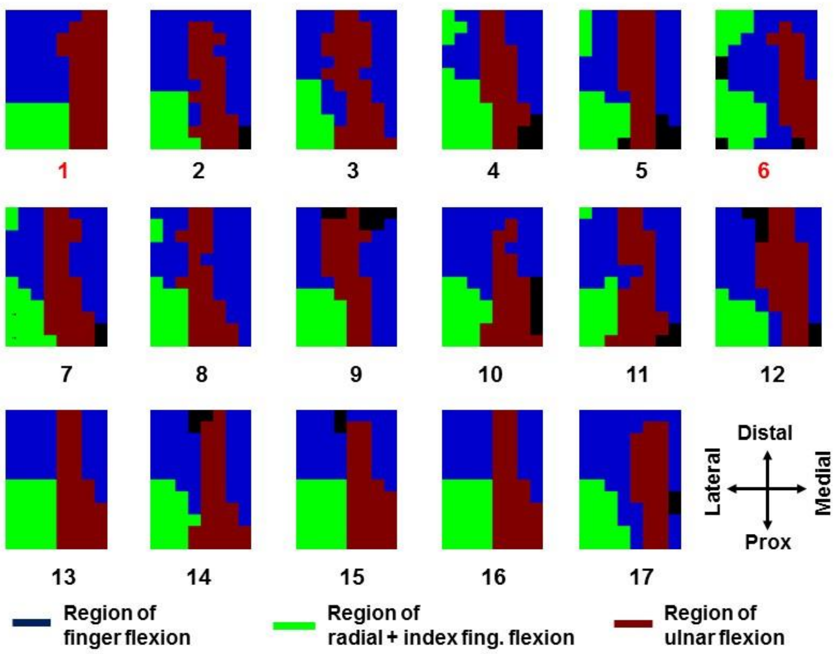
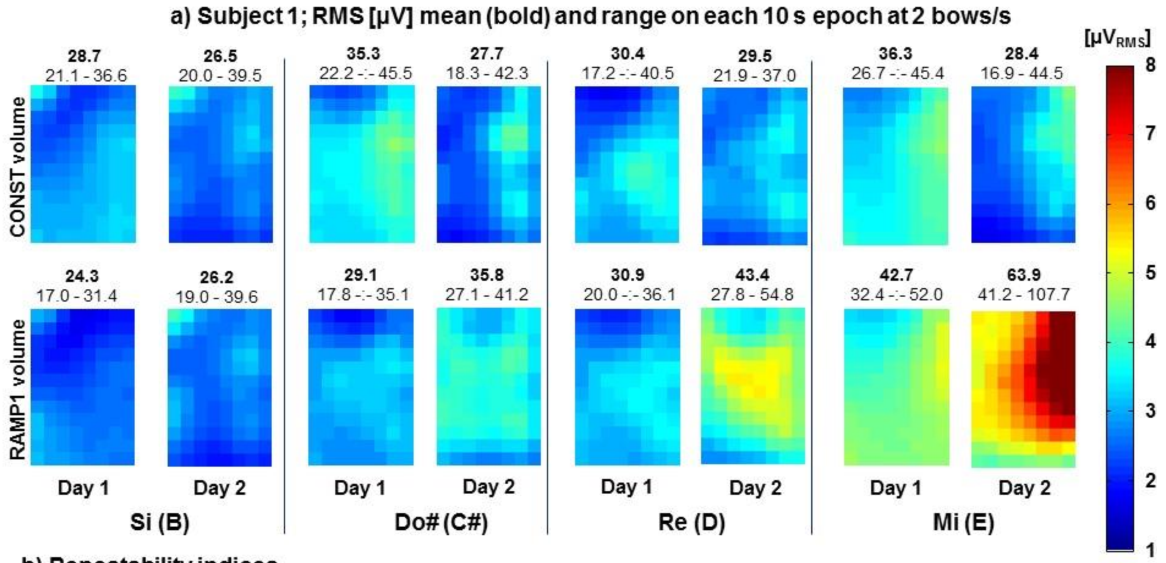


Fig. 3. Reference templates for the 17 subjects obtained as indicated in Fig. 2g.



b) Repeatability indices

MSD Day 1 - Day 2	CONST volume abs	CONST volume rel	RAMP1 volume abs	RAMP1 volume rel
Si (B)	0,028	16%	0,035	21%
Do# (C#)	0,025	15%	0,012	7%
Re (D)	0,012	7%	0,016	9%
Mi (E)	0,040	24%	0,069	41%

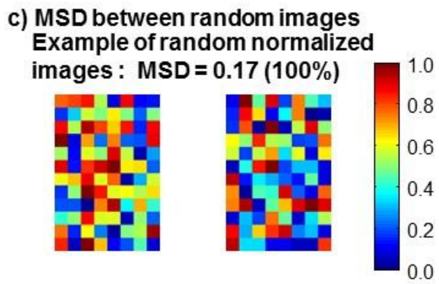


Fig. 4. a) RMS-images over 10 s epochs obtained from subject 1 in day 1 and day 2 for CONST and RAMP1 sound volume and for the four notes. The mean and the range of the RMS of the pixels (in space) of each image are indicated in μV_{RMS}. b) Absolute and relative (with respect to the 0.17 reference corresponding to a random image) *MSD* values, defined in eq. 2, of the RMS-images between day 1 and day 2. c) Examples of two random images (pixel values taken from a uniform distribution between 0 and 1) and corresponding mean value of *MSD*. This value is taken as a reference for the *MSD* values reported (in % of 0.17) in b). Se section 2.5.2 for further details.

3.2.2. sEMG RMS images in RAMP tasks

The RAMP1 task was repeated after 5 min of demanding free playing exercise without removing the electrodes (RAMP2). Pre- and post-exercise analysis of sEMG confirmed electrode stability and good signal quality.

Pattern repeatability between pre- and post-exercise RAMP tests was assessed using, as indicated in 2.3.1 and 2.3.2, a) the distance between the normalized histograms (eq. 1), and b) the mean square difference (*MSD*) between images normalized with respect to the respective maximum (eq. 2).

Table 2 shows the values of the repeatability index R_{ind} defined in eq. 1. Histograms which differ by less than 15% of the ROA pixels are outlined. It is evident that most subjects repeat the same note, after 5 min of playing, using different muscle activation patterns.

Table 3 shows the values of the repeatability index *MSD*, defined in eq. 2, for the 17 subjects and the four notes. The two indices provide different information. R_{ind} is a new tool associated to the ROA and defines the involvement of different muscle groups by comparing each ROA with the corresponding reference image provided in Fig. 2 and Fig. 3. MSD is a more traditional tool which compares each entire pre-exercise image with the entire post-exercise image. 100% MSD is associated to two random images (section 2.5.2 and Fig 4c).

Table 2. Repeatability index (*Rind*, defined in eq.1) computed for each subject and each note between the two RAMP tasks pre- and post- exercise (RAMP1 with respect to RAMP2). Histograms whose Euclidean distance $R_{ind} \leq 10.6$, corresponding to a sum of absolute deviation ("city-block" distance) less than 15% of the ROA are outlined in grey. For this threshold, only subjects 8 and 13 show similar pre- post- exercise histogram for all the four notes. Subjects 6, 9 and 17 show similar pre- post- exercise histograms for three out four notes. The other subjects show more relevant differences.

		Subjects																
	R_{ind}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Note played	SI	21,3	41,8	62,9	37,4	81,6	37,7	7,1	5,6	16,4	17,4	32,9	57,3	0,0	78,8	0,0	28,3	0,0
	DO	10,8	10,0	59,5	11,8	28,8	2,5	36,2	2,2	7,2	87,1	8,1	11,5	0,0	19,9	81,0	18,7	0,8
	RE	14,6	23,8	17,9	53,0	10,4	8,7	23,2	2,5	6,4	35,6	15,2	13,8	7,3	1,6	19,1	19,3	1,4
	MI	5,3	9,0	5,1	55,6	23,8	1,6	0,0	0,0	0,0	30,6	0,0	4,7	7,5	10,9	24,9	13,4	14,8

Table 3. Relative *MSD* with respect to a random image (see 2.5.2 and eq. 2) computed for each subject and each note between the two RAMP tasks pre- and post- exercise (RAMP1 with respect to RAMP2). Maps with a relative *MSD* less than 5% (100% correspond to the mean difference between two random images) are outlined in grey. For this threshold, only subjects 9, 13 and 17 show similar pre- post- exercise sEMG distributions for all the four notes. Subjects 2, 5, 6 and 16 show similar pre- post- exercise histograms for three of the four notes. The other subjects show more relevant differences.

	Relative *MSD*	Subjects																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Note played	SI	6,6	7,7	15,0	1,6	16,1	9,2	1,3	5,9	4,5	6,4	3,4	14,5	0,2	43,6	0,7	7,5	0,9
	DO	5,0	3,2	13,8	1,9	2,9	3,7	7,5	6,8	5,0	23,1	9,6	9,9	0,3	16,1	25,9	4,6	0,4
	RE	6,2	4,6	2,8	13,2	1,0	1,1	6,4	0,7	1,1	2,2	6,7	28,6	3,5	2,0	15,6	1,5	2,1
	MI	1,1	0,7	3,1	14,3	1,9	1,6	0,1	0,5	4,2	2,1	1,5	4,3	0,2	2,9	2,2	1,9	1,8

3.2.3 Repeatability on different days

For a few subjects it was possible to repeat the test in two days. Fig 4 shows the RMS-images obtained for the 10-s epoch in the two days, for the four notes and for the CONST and RAMP1 performances, for subject 1. Differences are clearly detectable both in sEMG signal intensity and in pattern. It is also evident from Fig. 4, as expected, that different notes imply different muscle activation patterns which are reasonably repeatable for the same note. Although the electrode grid was repositioned in the same marked location (Figure 1a), minor differences may be due the repositioning . See also section 3.4.

3.3. CONST and RAMP tasks time course

The slope of the CONST regression (either force or RMS versus time) was not significantly different from zero for any of the played notes and there was no statistically significant difference between slopes associated to 2 bows/s and 4 bows/s. This indicates that there are no RMS time trends in this condition.

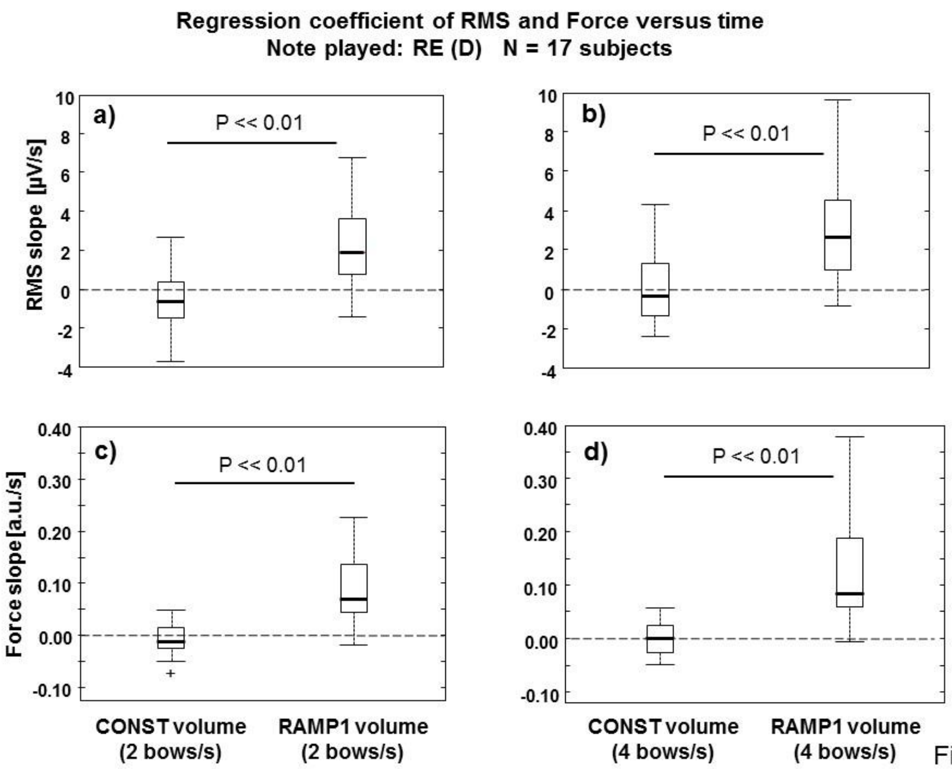


Fig. 5

Fig 5. a) and b) Box plots (median and quartiles) of the regression coefficient (slope) of the mean RMS value of ten 1-s RMS-images versus time for the conditions of CONST and RAMP1 volume at 2 bows/s and 4 bows/s. c) and d) box plots (median and quartiles) of the regression coefficient (slope) of the force pressing the second string (LA, A) in the same conditions as a) and b). One-way repeated measures ANOVA test. See section 2.8.

On the other hand, the difference between the regression coefficients in the RAMP1 and the CONST conditions was highly significant for all notes and both bow velocities ($p << 0.01$, section 2.8) both for force and for RMS. Fig. 5 shows the box plots (median and quartiles) of the slope values for note RE (D) played at 2 bows/s and 4 bows/s. The force applied to the string and the mean value of the RMS-images of the wrist and finger flexors of the left hand are, therefore, affected by the volume of the produced sound but not by the speed of the bow.

3.4. Inter-subject and inter-note variations based on ROA

Fig. 6 shows the histograms, defined in 2.5.1, for each of the 17 subjects playing the note SI (B), on the second string, with CONST (a) and RAMP1 (b) sound volume.

It is evident that, while playing the same note, different subjects use different sEMG activity patterns which result in different RMS-images.

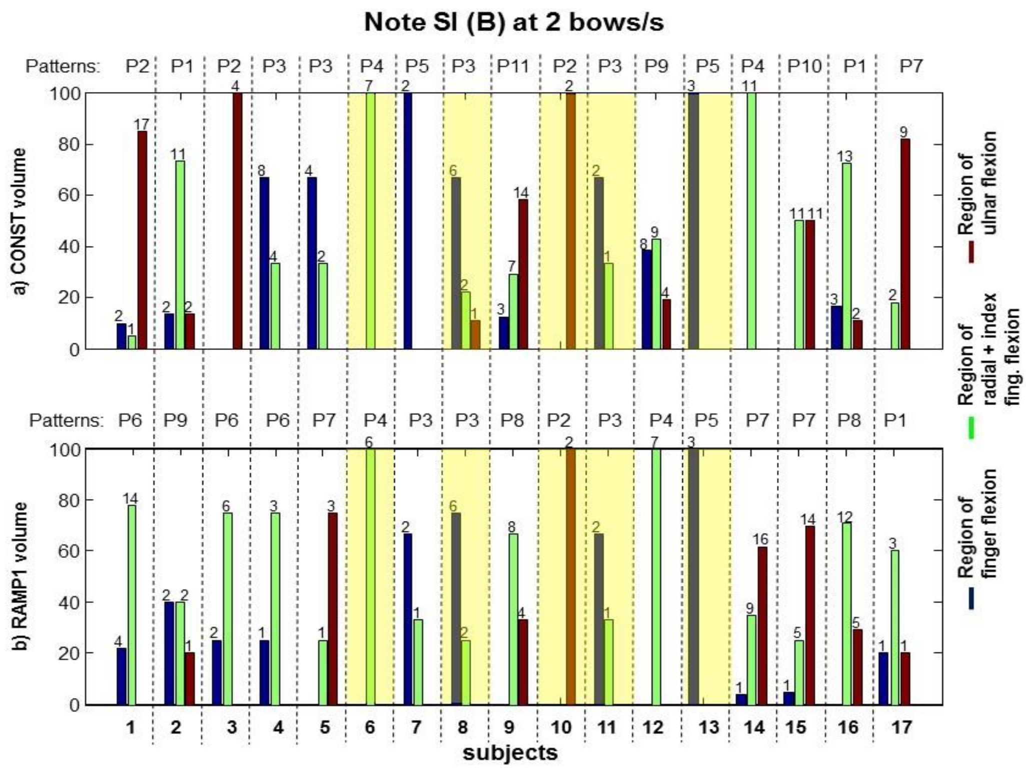


Fig 6. Three-bar histograms (defined in 2.5.1) for the 17 subjects playing note SI (B) with CONST and RAMP1 sound volume. The value near each bar indicates the number of pixels of the ROA belonging to region 1, 2 and 3 of that subject, as defined in Fig. 2g and in Fig. 3. The sum of these three numbers is the number of pixels of the ROA. The y axis provides the same information expressed in percentages of the ROA area belonging to region 1, 2, and 3 of each subject. Eleven different patterns can be identified by visual examination. The subjects outlined with the light colored background show similar patterns in the CONST and RAMP1 tasks.

identified by visual analysis of the three-bar histograms (P1 to P11). Only five subjects activated their muscles with very similar patterns in the CONST and in the RAMP1 tasks. They are indicated with the light colored background. The other 12 subjects substantially changed the pattern of activation of the ***left*** finger and wrist flexors as they increased the sound volume by increasing the pressure of the bow held with ***right*** hand.

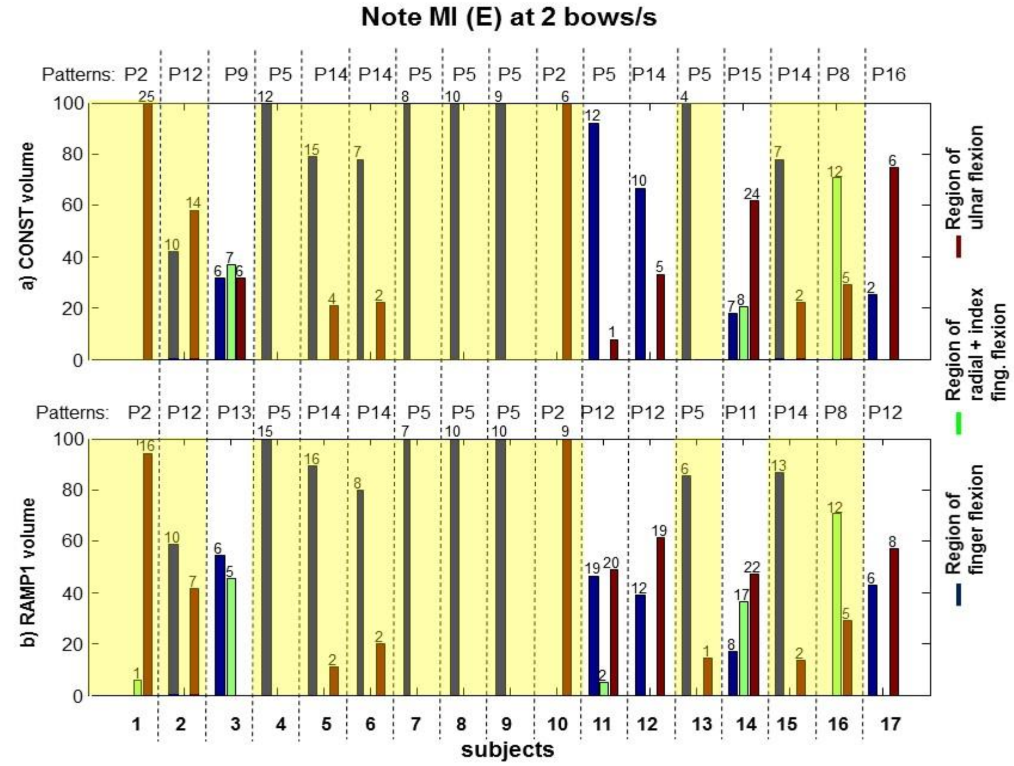


Fig. 7. Three-bar histograms (defined in 2.5.1) for the 17 subjects playing note MI (E) with CONST and RAMP1 sound volume. See Fig. 6. Five new patterns have been identified in addition to some of those defined for note SI (B). In total 16 different patterns have been identified for these two notes. The subjects outlined with the light colored background show similar patterns in the CONST and RAMP1 tasks.

3.5. Force, sound and sEMG in bowing up and down

The sound recording shows a sudden change when the bow reverses direction. This change allows the separation of the bow-up from the bow-down swings which last about 0.5 s each with a bow excursion of 15-20 cm. Fig. 8a shows the RMS-images associated to the 10 bow-ups and to the 10 bow-downs epochs during the RAMP1 task performed by subject 1 playing the note SI (B). Panel b) shows the force signal applied to the second string. The bow-ups and bow-downs are clearly distinguishable from the sound signal depicted in panel c). It is evident that this subject releases the pressure applied to the string each time the bow is at its lowest point and is changing direction.

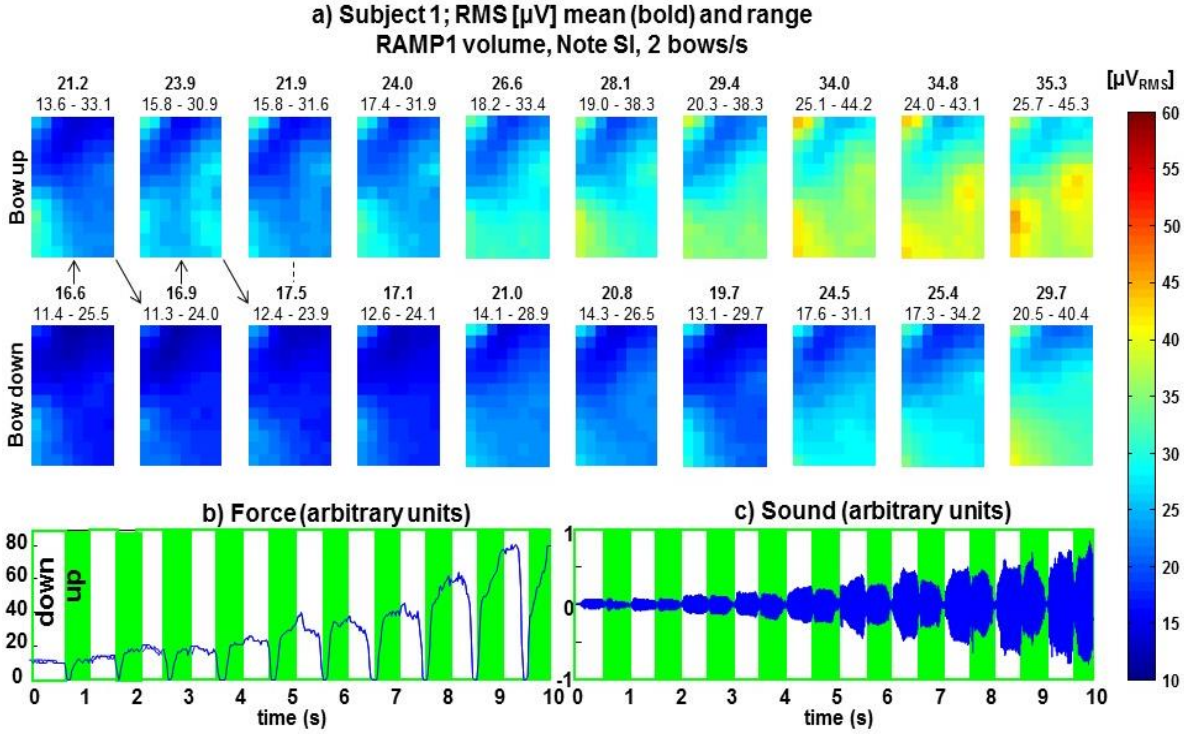


Fig. 8. a) RMS-images computed over epochs of about 0.5 s corresponding to the bow-ups and bow-downs of subject 1 playing note SI (B) at 2 bows/s during the RAMP1 task, b) pattern of force applied to string 2, c) sound intensity produced. The small gaps in the sound intensity are used to define the bow-up and bow-down intervals. Note the release of force applied to the string at the end of each bow-down phase. This pattern is typical of this subject.

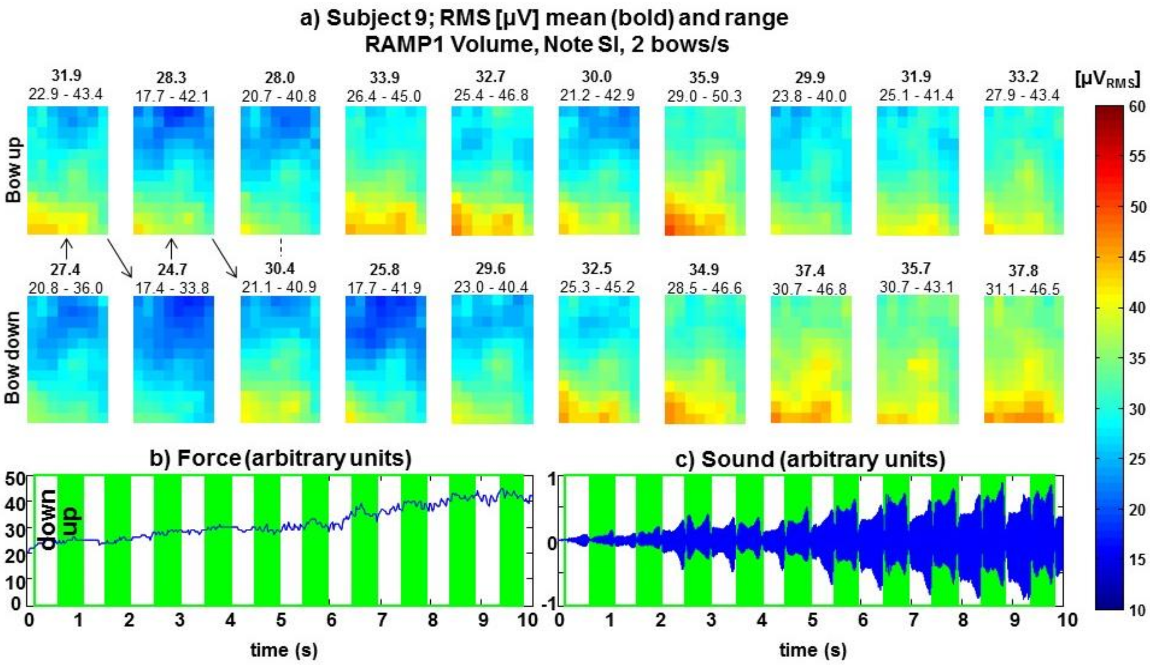


Fig. 9. Same as Fig. 8 for subject 9. Note the very different force patterns with respect to subject 1. Other subjects show different patterns including substantially constant force patterns.

This causes a small gap in the sound. It is also evident that the median, the range and the distributions of RMS-images are different during the bow-ups with respect to the bow-downs.

Fig. 9 shows the same information for subject 9 whose patterns of sEMG and force are very different from those of subject 1. Other subjects show different patterns indicating that the same note is, in general, played by different subjects in different ways implying different force and sEMG patterns.

3.7 Surface EMG differences between notes based on MSD

A one-way ANOVA was performed, for each note, to compare the *MSD* values described in section 2.5.2 (i.e., SI vs SI with respect to SI vs All etc.). A highly significant difference was found for each comparison ($p << 0.01$) indicating, as expected, that the effect due to the note is much higher than the effect due to the conditions.

For each subject the sEMG spatial distribution associated to each note is consistent and distinguishable from that associated to another note , although it is different from subject to subject and from condition to condition (e.g., bow velocity, sound volume, pre-post exercise).

4. Discussion

No other report has been found, in the peer-reviewed literature, concerning the distribution of sEMG activity in the left forearm of violin players. Although such distribution represents an estimate affected by a number of limitations (see section 6), it provides a semi-quantitative assessment of the activation patterns of the left forearm wrist and finger flexor muscles by a violin player while playing different notes on the second string. This is a "proof of concept" study showing that HDsEMG differences can be detected among different subjects playing different notes. This fact provides preliminary evidence justifying further investigations to define thresholds and classify conditions or subject groups.

Detection system. The monopolar detection system adopted in this study provides a detection volume larger than that associated to single or double differential or Laplacian detection systems[2]. It has the advantage of detecting signals from deep portions of the muscles of interest (Fig. 1b) and the disadvantage of being sensitive to the activity of other muscles at some lateral distance from the electrode grid.

Remote (possibly antagonist) muscles may contribute with crosstalk signals (mostly common mode) as shown in Fig. 1d. The issue of crosstalk has been addressed in the literature[20, 21] and deserves further investigation. Other detection systems would have greater spatial selectivity and privilege superficial sources closer to the electrode array. The availability of monopolar signals allows the future calculation of spatially filtered signals.

Reference sEMG images and normalization. A flexible electrode grid, applied to the volar side of the forearm, reliably collects sEMG signals and provides RMS-images describing the activities of the underlying muscles. Images associated to isometric low level radial or ulnar flexion of the wrist and to flexion of the different fingers have been used as topographical individual templates for the classification of RMS-images collected during playing different notes on the second string of a violin. It is underlined that two images that differ only by an amplitude scaling factor are considered equal and only topographical differences are detected and classified. At this preliminary stage, classification of patterns (Fig. 6, Fig. 7) was done by visual analysis and not by mathematical algorithms.

Intra- and inter-subject variability. A number of indicators of topographical differences between RMS-images can be used to investigate this issue. The two indicators that have been used in this study point out both intra- and inter-individual differences. Such differences are remarkable, indicating that different muscle strategies are implemented not only by different subjects but also by the same subject, when repeating the same task. Table 2 shows that when a RAMP volume is repeated twice, without removing the electrode array, most subjects show different ROA patterns. Table 3 shows the mean square differences (MSD) between the two entire images corresponding to the two RAMP tasks. In both cases a normalization process is adopted and a threshold is used to differentiate between the ROAs or between the images being compared. The results depend on how these thresholds are chosen (see section 6). The differences between the RMS images associated to RAMP1 and RAMP2 are unlikely due to fatigue (low effort for a short time); more likely they reflect different strategies adopted by the CNS of the player to obtain the same result when repeating the same task. This issue deserves further investigation.

Isometric reference contractions of the muscles in question provide rather similar distributions of sEMG activity under the electrode grid across subjects, as shown in Fig. 2 and 3. This is not necessarily the case when the same note, either SI (B), DO# (C#), RE (D) or MI (E), is being played, either at 2 bows/s or at 4 bows/s, in CONST or RAMP conditions. Different subjects present different levels of intra-subject variability.

This observation points out that the same musical task or performance can be obtained with different muscle activation patterns (Fig 4, 6 and 7). Whether this finding represents a positive or negative point with regard to muscle fatigue and development of PRMD remains to be investigated.

Effect of sound volume. In most subjects the force applied by the left fingers to the string and the sEMG distribution of the left wrist and finger flexor muscles depend on the sound volume. In turn the sound volume is determined by the pressure, the speed and the contact point of the bow controlled by the right arm. A variety of different force and sEMG patterns have been observed during CONST and RAMP tasks. Two very different cases are reported in Fig. 8 and Fig. 9 for the RAMP task. This finding justifies further studies to clarify the relevance of this right-left association.

5. Conclusions and future perspectives

The main conclusion of this study is that the HDsEMG technology is suitable for investigating forearm muscles in musicians and its further refinement is justified. Its current technical limitations (see section 6) should be overcome in order to provide musicians with user-friendly biofeedback instruments for training, as suggested more than 30 years ago by LeVine[12] and Morasky[11]. This technique will likely increase body awareness and performance level of the artist and possibly reduce PRMDs.

A second conclusion is that the amplitude of the sEMGs produced by the left muscles pressing the strings, as well as the pressure applied by the fingers to the strings, increase as the sound volume, controlled by the right arm, increases. Such sEMG and pressure increase is different in different subjects. Whether this is a positive or negative fact for the artist’s health remains to be investigated.

This study addresses a limited number of issues concerning the muscle strategies adopted in playing four notes on the second string of a violin. Only the activities of the wrist and finger flexor group are reported. Within these boundaries, a third conclusion is that the ROA associated to each note is not necessarily the same when the same task is repeated, however the sEMG maps corresponding to different notes are distinguishable within and between subjects.

These conclusions raise a number of research questions that should be investigated in future work.
Does an optimal pattern of muscle activity, in terms of a) minimization of force and fatigue or b) optimization of performance, exist? If such pattern does exist, is it an individual or a general pattern? In either case how can a musician be trained to adopt or enhance it while avoiding incorrect and potentially dangerous patterns? Answering these questions has an obvious impact on teaching strategies as well as on the prevention of PRMD.

6. Limitations of the work

This study is preliminary and semi-quantitative. Its purpose is to show the suitability and potential role of HDsEMG in the study of the left forearm muscles of violin players. This work is affected by a number of limitations listed below and demonstrates that it is worth to overcome them in the near future.

1. The interelectrode distance (10 mm) is a borderline value and should be smaller (about 5-8 mm)[22].
2. The area covered by the electrode grid should be larger to completely cover muscles that were only partially covered in this study, displaying evident truncation of the sEMG distribution (Fig.2 and Fig. 4). This implies a substantial increase of electrode number and advancements in the current detection technology that should provide a sleeve with an electrode grid covering the entire forearm with 5-8 mm inter-electrode distance. Signals from wrist and finger extensor muscles need to be detected simultaneously with those from the flexor muscles.
3. Only one violin string has been investigated. The muscle activity associated to the other strings should be studied and force sensors with larger sensing area should be developed and used.
4. Possible individual anatomical variations should be investigated more deeply by means of ultrasonic techniques for the identification of the individual muscles and of subcutaneous tissue thickness. This additional information would allow more accurate interpretation and modelling of the detected HDsEMG.
5. Open issues related to crosstalk between muscles[20, 21] should be solved to allow a more selective identification of the sEMG contributions of individual muscles. Other detection systems (single and double differential and Laplacian) should be investigated as well as decomposition techniques for the separation of contributions from different muscles[2].
6. Thresholds and pattern classification criteria are somewhat subjective in this study and should be defined in a more rigorous way.

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