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The practice of a musical instrument requires fine dexterity, repetitive, fast, and precise movements, as well as important efforts to set the instrument into vibration, while adopting postures often unnatural for the human body. As a result, musicians are often subject to pain and musculoskeletal disorders. In the case of plucked string instruments and especially the concert harp, the plucking force is directly related to the strings' tension. Consequently, the choice of the strings has to be made based on both, the musician feel while playing, and the musculoskeletal consequences. This paper investigates how the string properties and the playing dynamics affect the finger and wrist muscle activity during harp playing. This study first emphasized the noteworthy recruitment of the flexor and extensor muscles (42 % and 29 % of MVC, respectively). Findings outlined further that the fingering choice, the adopted playing dynamics and the string's material govern the muscular activity level and the playing control. Such results are a first step to better understand how the harp ergonomics may affect the player's integrity and help them decide the most suitable stringing for their practice.

Keywords: Concert harp; Electromyography; Biomechanics; Stringing

Introduction

Musical performance requires a wide range of cognitive, physiological and musical skills such as instrument-specific motor skills and ability to repeat highly controlled motions (Cohen & Bodner, 2019; Matei & Ginsborg, 2017). This physical commitment makes musicians prone to "playing-related musculoskeletal disorders" (PRMD) (Rotter et al., 2020; Zaza, 1998). Surveys have been conducted on professional musicians, revealing that more than 75 % of them suffer from PRMD (Gasenzer et al., 2017; Kok et al., 2016; Middlestadt & Fishbein, 1988). Muscular disorders include in particular muscle-tendon unit overuse syndromes, and muscle imbalance movement impairment syndromes (Caldron et al., 1986). Neuromuscular disorders include focal motor dystonia, cervical radiculopathy, radial neuropathy and thoracic outlet syndrome (Bejiani et al., 1996). As evidenced by the epidemiological study conducted by Martin (2013), 74 % of harpists reveal pain, mainly located in the upper back, neck, and shoulders. Martin (2013) assumed that harp strings tension is directly involved in the musculoskeletal pain occurrence through the required muscular activation. This assumption is reinforced by Moraes & Antunes (2012), underlining that an excessive muscle tension is a factor of pain occurrence.

Musicians are looking for posture and techniques optimization to prevent PRMDs by avoiding unnecessary efforts and muscle co-contractions (Bejiani et al., 1996; Caldron et al., 1986). Training procedures are also explored to improve the musician's force, and precision (Gorniak et al., 2019; Muramatsu et al., 2022). To obtain quantitative insights, a few biomechanical studies have been recently published (Blanco-Piñeiro et al., 2017; Goubault et al., 2021; Metcalf et al., 2014; Park et al., 2019). Kinematics has mostly been interesting to address playing posture and ancillary gestures (or accompanist gestures) (Wanderley et al., 2005). Further, exploring biomechanical loads through inverse dynamic procedures is of great interest to approach PRMDs. Investigating violin performance, Visentin & Shan (2003) showed that the right shoulder loads vary according to the string played, whereas wrist and elbow loads remain constant. Costalonga et al. (2019) developed an apparatus to study the forces applied by the left-hand fingers while playing guitar. High frequency notes require a higher range of forces on each string (2 to 10 N) than low frequency notes. Finally, surface electromyography (EMG) is a common method to address musical performance

(Baeyens et al., 2020; Cattarello et al., 2017; Duprey et al., 2017; Itoigawa, 2019; Mann et al., 2021; Russo et al., 2019; Steinmetz et al., 2016). Several studies focused on bow string instruments. Focusing on the sound producing gestures, Duprey et al. (2017) and Cattarello et al. (2017) investigated relationships between playing techniques and forearm muscular activation. Further, violinists with playing-related neck pain demonstrated for instance a greater sternocleidomastoid muscle activity than violinists with no pain (Steinmetz et al., 2016). Muscular activity during piano performance has also been investigated with respect to playing techniques and risk of PRMDs (Chong et al., 2015; Degrave et al., 2020; Goubault et al., 2021; Oikawa et al., 2011). Nevertheless, no clear evidence of a relationship between muscular activation and PRMDs has been provided to date (Overton et al., 2018).

The concert harp is one of the instruments with the highest strings tension: 200 to 500 N (Chadefaux, 2012). Using high-speed camera and optoelectronic systems, harpists have been shown to adopt a common posture, and provide specific but highly repeatable upper-limb and fingering movements (Chadefaux et al., 2012, 2013, 2014). One of our preliminary studies has shown that the plucking action requires the harpist to solicit the entire kinematic chain of the upper-limb (Chadefaux et al., 2013). These complex gestures and body strategies induce significant muscular efforts, which can lead to a long-term development of musculoskeletal disorder. Therefore, the choice and the settings of each maker's elements (strings, soundboard, and soundbox) are a compromise to optimize both the sound and the playability of the instrument, while seeking a good static resistance of the structure over time. In particular, the many possibilities of string properties (e.g. materials, gauges, lengths, manufacturing process) are very useful for defining this optimum. This diversity makes, paradoxically, the instrumentalist powerless to the choice of new strings.

Under this framework, the present study aims at understanding how the harp string properties and the playing dynamics affect the harp performance. Although the PRMD related to harp performance are mainly located in the upper back, neck, and shoulders, emphasis is placed on the forearm muscles activity to focus on the wrist and finger motion, reflecting mostly the sound producing gestures. Our hypothesizes are that (1) flexor muscles are more activated than extensor muscles when playing harp; (2) increased dynamics underlie increased muscular activation; and (3) the higher the string's tension, the greater the muscular activation.

To address these hypotheses, an experiment has been carried out with harpists, addressing the activation of four right forearm muscle sites with respect to various strings, playing dynamics and stringing materials.

Methodology

Participants

Nine participants (eight females and one male, 37.3 ± 16.3 years old, Height 1.67 ± 0.04 m, Body mass 61 ± 5 kg) without noteworthy pathology were involved in the three sessions of the experiments. All participants were regular harp players (five harp teachers, four amateurs), with at least 10 years of experience, and practiced in average about 6 hours per week. The experiment is in agreement with the Declaration of Helsinki and all the participants signed an informed consent form.

Concert harp

Participants were asked to play on a concert harp (CAMAC Harps, Atlantide Prestige model, see Figure 1). At each session, a new stringing was mounted on the concert harp (CAMAC Harps, Atlantide Prestige model): gut, nylon, fluocarbon. Accounting for the time needed to change and stabilize the stringing, each session took place on a different day. The study was focused on a set of four strings. The physical characteristics of these strings are provided in the Table 1.

Measurement protocol

At each session, participants were asked to perform three different musical sequences. The first sequence is constituted of 13 isolated notes executed at 80 bpm (see Figure 2). The sequence was repeated three times. Then, the second sequence consisted into an arpeggio sequence (see Figure 3). The sequence was performed at 80 bpm under three different dynamics (*Piano*, *Mezzoforte*, *Forte*) according to the participant's judgement. The sequence was repeated five times at each dynamics in a randomized order to avoid fatigue or learning effect. Note that the fingering was imposed for these two first sequences: the ring finger, the middle finger, the index finger, and the thumb plucked the strings 30, 29, 27 and 24, respectively. Finally, a short musical excerpt was performed: the 6th variation of the *Gimblette* by Bernard Andrès. The sequence was repeated as many times as required to reach to the best performance according to the participant's feel. Only the last performance was analyzed for the present paper. A whole session lasted about two hours where the participant played the harp for 30 to 45 minutes.

String vibration

The bidimensional movement of the four studied strings (Table 1) was measured using optical sensors (OPB815L OPTEK Technology Inc., Woking, United Kingdom, sampling rate at 25600 Hz) fixed close to the instrument mechanism (Le Carrou et al., 2014) (see Figure 1). These signals were used to point out each note onset, i.e. the instant where each string starts oscillating after the plucking action.

Soundboard vibration

The resulting soundboard vibration was simultaneously measured with two single-axis accelerometers (PCB Piezotronics, Saint-Aubin, France, SN 352C65, 50 g pk, [0.5 – 10,000] Hz, sampling rate at 25600 Hz) located at the back of the soundboard. Accelerometers were fixed between the strings 24 and 27, and between the strings 29 and 30. The first accelerometer was used to study the strings C♭1 and G♭1, while the second was dedicated to the strings E♭2 and D♭2. Finally, the root-mean-squared (RMS) acceleration level was computed over a 500 ms window from the note onset. This variable is referred to as L.

Muscular activation

The plucking action consists mostly into a movement of fingers flexion associated to a combination of wrist flexion/extension and abduction. Consequently EMG signals from four forearm muscles (the flexor digitorum superficialis (FDS), the flexor carpi radialis (FCR), the extensor digitorum communis (EDC), the extensor carpi radialis (ECR)) were collected using a wireless system (Delsys Trigno, Natick, MA, USA, sampling rate at 1925 Hz) (see Figure 1). Electrodes were positioned after appropriate skin preparation on the muscle bellies. First, recommendation proposed by (Cram, 2011) were followed to identify the optimal electrode position. Then, to refine the electrode position, muscle bellies were palpated while participants performed wrist and finger isometric contractions. These tasks were separated into flexion and extension of the wrist only and flexion and extension of the fingers only. This step was monitored to verify the correct placement of the electrodes and to minimize cross-talk issues. Finally, when seated, each participant realized maximal voluntary contraction (MVC) tasks to evaluate the capacities of the four investigated muscle groups. MVC tasks for FDS and EDC consisted into fingers maximal exertions in flexion and extension while keeping the four long fingers together. MVC tasks for FCR and ECR consisted into wrist maximal exertions in flexion and extension while keeping the fingers relaxed to avoid extrinsic finger muscles contribution. Participants were verbally encouraged during each MVC task. Each MVC task lasted five seconds, followed by a resting time of a minute, and was repeated twice.

EMG signals passed through a bandpass filter and full-wave rectifier with zero phase shift ([20--400] Hz; 4th order Butterworth). The associated RMS signals were then calculated using a 500 ms moving window (Valero-Cuevas et al., 1998). For each electrodes, the resulting signals were normalized by the maximal values measured during the MVC tasks. Then, the RMS level of each forearm muscles activity during the plucking action was computed over a 300 ms window before each note onset. The window duration has been chosen based on the averaged plucking action duration (Chadefaux et al., 2012). This variable is referred to as A^{emg} where emg = {EDC, ECR, FDS, FCR}.

Muscular co-contraction

To get insight into the playing control, especially regarding joint stabilization, the muscular co-contraction was computed as the ratio between the extensor and flexor muscles RMS level of activation. In particular, the co-contraction indicator has been derived as $(A^{EDC}+A^{ECR})/(A^{FDS}+A^{FCR})$.

Statistics

In order to describe the forearm muscles activity during a concert harp performance, each previously defined variable was investigated regarding the played strings, the playing dynamics, and the stringing material. Given the sample size (nine participants), the nonparametric Friedman's test with repeated measures were carried out to highlight the effect of the playing dynamics and the stringing material on the forearm muscles activity. When a significant effect was observed ($p < 0.05$), a multiple comparison post-hoc test (Nemenyi test) was carried out to determine the conditions leading to significant differences.

Results

In the following, the isolated notes sequence was only investigated to get insight into the muscular activation patterns. The study focused on the arpeggio and the musical excerpt sequences to get closer to a real harp performance.

Muscular activation patterns

Figures 2, 3 and 4 present specific samples valuable to describe the muscular activation patterns during harp playing. The sample selection was made in order to show representative patterns with respect to the entire database.

Considering the isolated notes sequences, the four investigated muscle sites showed a similar activation signals throughout the plucking actions, whatever the stringing material (see Figure 2). From one note onset to the next, the muscular activation signals presented first a rest period before an increase up to a maximum value and finally a decrease back to a minimum value at the note onset. This entire pattern lasted about 3 seconds, which corresponds to the duration between two notes' onset at the imposed *tempo*. During this time period, the participant plucked and muffled the strings. The increase/decrease sequence in the muscular activation reflected therefore the strings' muffling.

Regarding further arpeggio sequence, the four forearm muscle sites investigated presented specific but repeated activation signals accross the dynamics and the stringing materials (see Figure 3). Unlike the isolated notes sequence, no resting period occurred in the arpeggio sequence. Indeed, to play a group of four consecutive notes, the hand was fixed and the fingertips were pressed on the strings. As a result, the muscular activation never decreased as for playing isolated notes, and signals were less straightforward to relate to the score. Accordingly to the isolated notes sequence, the note onset occurred during the decreasing phase of the activation pattern.

From a more general perspective, each participant showed specific and repeatable muscular activation patterns. Each participant also owns his particular muscular recruitment strategies. To illustrate, Figure 4 shows that Participant A favored the use of the flexor muscles with respect to the extensor muscles, while Participant B mostly recruited fingers' muscles with respect to the wrist's muscles. A non negligible variability existed in the activation patterns developed by each musician. However, this variability appeared to be lower than the one observed from one harpist to the other.

Investigating further the averaged activation level of FDS, FCR, EDC and ECR while playing harp, the flexor muscles activation was outlined higher than the extensor muscles activation. In a lesser extent, finger muscles' activation was slightly higher than the wrist muscles activation. Indeed, performing isolated notes A^{FDS} and A^{FCR} reached about 44 % and 37 % of the MVC, while A^{EDC} and A^{ECR} reached about 23 % and 20 % of the MVC. Similarly, performing arpeggio, A^{FDS} and A^{FCR} reached about 47 % and 37 % of the MVC while A^{EDC} and A^{ECR} reached about 30 % and 27 % of the MVC.

Soundboard vibration

The RMS acceleration of the soundboard vibration was consistent with the imposed dynamics (see Figure 5). Significant differences between each three dynamics ($\chi^2 = 1319$, $df = 2$, $p < 0.01$) and each three stringings ($\chi^2 = 147$, $df = 2$, $p < 0.01$) occurred. As expected, the lowest and the highest RMS values were obtained for the

Piano and *Forte* conditions, respectively. Regarding the stringing materials, Nylon strings presented a significantly lower RMS value than Gut and Fluocarbon strings. No difference appeared between Gut and Fluocarbon strings.

String effect

Forearm muscle activation was significantly affected by the four investigated strings (FDS: $\chi^2 = 128$, df = 3, $p < 0.01$; FCR: $\chi^2 = 360$, df = 3, $p < 0.01$; EDC: $\chi^2 = 192$, df = 3, $p < 0.01$; ECR: $\chi^2 = 349$, df = 3, $p < 0.01$). In particular, Figure 6 reveals a significantly lower forearm muscle activation when plucking the string 29 regardless of the muscle. The RMS level of FDS was increased when plucking the strings 27 and 24 compared to the strings 30 and 29. On the opposite, the RMS level of FCR was measured higher when plucking the strings 30 and 24 than the strings 29 and 27. Besides, the activation of the extensor muscles appeared slightly higher when plucking the strings 27 and 24 than the strings 30 and 29.

Dynamics effect

Figure 7 highlights significant differences between the RMS level of the four forearm muscles activation with respect to the dynamics conditions (FDS: $\chi^2 = 860$, df = 2, $p < 0.01$; FCR: $\chi^2 = 851$, df = 2, $p < 0.01$; EDC: $\chi^2 = 569$, df = 2, $p < 0.01$; ECR: $\chi^2 = 108$, df = 2, $p < 0.01$).. Regardless the forearm muscle, the RMS level of muscular activation significantly increased with the dynamics condition. More specifically, $A^{(FCR, FDS)}$ increased more rapidly than $A^{(ECR, EDC)}$ with respect to the playing dynamics (increase of 76 % versus 42 % in average from the Piano to Mezzoforte).

Moreover, Figure 8 indicates a significant decrease in the co-contraction from the Piano to the Forte dynamics ($\chi^2 = 184$, df = 2, $p < 0.01$).

Stringing material effect

Figure 9 shows significant differences between Nylon, Gut and Fluocarbon strings (FDS: $\chi^2 = 262$, df = 2, $p < 0.01$; FCR: $\chi^2 = 353$, df = 2, $p < 0.01$; EDC: $\chi^2 = 59$, df = 2, $p < 0.01$; ECR: $\chi^2 = 113$, df = 2, $p < 0.01$).. $A^{(FCR, FDS)}$ reached values from about 25 % and 55 % of the MVC. The RMS level of extensor muscles activation reached about 23 % of the MVC regardless the stringing materials. Aside from an activation of ECR reaching about 40 % of the MVC when playing Nylon strings, the same orders of magnitude were observed when playing arpeggio. The RMS level of flexor muscles activation was increased when playing Nylon and Fluocarbon strings compared to Gut strings. Regarding the RMS level of extensor muscles activation, Nylon strings induced a lower activation of EDC and a higher activation of ECR with respect to Gut strings and Fluocarbon strings.

Figure 10 reveals a significant effect of the stringing material on the co-contraction ($\chi^2 = 355$, df = 2, $p < 0.01$), especially a general decrease from Gut strings to Nylon strings and Fluocarbon. However, only Gut strings presented a significant higher muscular co-contraction with respect to the Nylon and the Fluocarbon strings, the co-contraction reached about 1.2.

Musical excerpt performance

The analysis of the *Gimblette* performance outlined that the RMS level of flexor muscles was increased from Gut strings to Nylon strings and Fluocarbon strings (see Table 2). Aside from Nylon strings that induced a slight deviation (A^{EDC}(*Nylon*) < A^{EDC}(*Gut*, *Fluocarbon*) and A^{ECR}(*Nylon*) > A^{ECR}(*Gut*, *Fluocarbon*), the RMS level of the extensor muscles presented similar values when playing with Gut and Fluocarbon strings.

Discussion

The muscular activation patterns revealed an important involvement of FDS, FCR, EDC and ECR during harp plucking (about 47 %, 37 %, 30 % and 27 %, respectively). As expected according to the harp plucking gesture, flexor muscles were more activated than extensor muscles. As already observed by (Itoigawa, 2019) during guitar performance, the note onset occurred during the muscular activation decrease rather than at its maximal value. This result is most likely explained by the plucking action description. Indeed, as previously outlined, the string is first pulled from its resting position before slipping over the finger surface up to the note onset (Chadefaux et al., 2012).

Additionally, the flexor muscles activation slightly decreased when accounting for an entire musical excerpt while no difference occurred regarding the extensor muscles. On the contrary, Chong et al. (2015) shown that muscular activity was increased when playing sequential task than isolated notes on a keyboard. One explanation is that the evolution we measured is due to the playing dynamics, probably close to *Mezzoforte* with respect to the muscular activation values, which was not imposed during the *Gimblette* interpretation. A second explanation is that the muscular activation computation accounts for the whole performance, including ancillary gestures, minimizing therefore the estimation.

Comparing our findings to the order of magnitude measured during other musical performance outlined the relatively high muscle activation levels required to play harp ($A^{(FDS,\ FCR)}$ and $A^{(EDC,\ ECR)}$ reached about 42 % and 29 % of the MVC). Indeed, the RMS values computed over a 300 ms before the note onset were higher than the peak values estimated for FDS and EDC during guitar (about 20 % of MVC for the two muscle sites (Itoigawa, 2019)) and piano performances (up to 35 % and 20 % of

MVC for FDS and EDC, respectively (Degrave et al., 2020)). This outcome is most likely explained by the simultaneous involvment of all the fingers positionned on the strings, when playing harp. Further, as previously stated, the concert harp is one of the instruments with the highest strings tension, conveying to plucking force up to 30 N (Chadefaux et al., 2012). Although the plucking action is of short duration, they are repeated numerous times, and such muscular recruitment draw attention to the harpist's risk of PRMDs.

Considering how the string played affect the forearm muscular activity outlined mostly the effect of the finger used. During the arpeggio sequence, harp players adopts a position where the upper-limb joints remain still to play a group of four consecutive notes. As a result, when plucking the strings 30 to 24, only the fingers are moving. At the beginning of the sequence, the four fingers are placed on the strings to stabilize the hand. As the notes are played, the fingers are not repositioned on the strings (see pictures proposed Figure 3). Consequently, the activation of the extensor muscles is increased to compensate the associated stability decrease. Likewise, because of the hand posture, FDS was more activated when playing the strings 27 and 24 than the strings 30 and 29. The index finger and the thumb are indeed placed almost along the string while the ring and the middle finger tend to be perpendicular to it. As a result, the movement of flexion is limited when playing the strings 30 and 29. Finally, results indicated an increased activation of FCR when plucking the strings 30 and 24 than 29 and 27. As these two notes are the transition notes between two groups of four notes, our understanding is that the wrist motion is governing this change of hand posture (Chadefaux et al., 2013), conveying to an increased flexor muscle activation. These results open up new perspectives of hand kinematics and joint organisation investigations.

The increase of dynamics has a direct influence on the forearm muscle activation. Regardless the muscle site, the activation is increased to apply a higher plucking force on the string and convey a louder note. Such result is in accordance with data reported by Itoigawa (2019) in guitar performance. Because of the muscle coordination during the plucking process, the flexor muscles activation are more increased than the extensor muscles activation. As a result, the co-contraction decreases while the dynamics increases. Indeed, the flexor muscles mostly drive the plucking action and its intensity, jeopardizing the joint stabilization and the plucking accuracy.

Regarding finally the string materials, the flexor muscle activation increased from the gut to the nylon and the fluocarbon strings. This result suggests that playing with gut rather than nylon or fluocarbon strings would be less strenuous for the flexor muscles. However, this result has to be moderated since a difference occurred in the soundboard vibration measured when plucking nylon strings with respect to gut and fluocarbon strings. On the opposite, an imbalance in the antagonist muscles activation would be assumed when playing with fluocarbon and, in a lesser extent, nylon strings. Further, the co-contraction decreased from the gut to the nylon and the fluocarbon strings. The precision-force trade-off conveys therefore that playing with gut strings allow a finer control from the harp player than nylon and fluocarbon strings. These outcomes are noteworthy to help players decide what stringing to mount on their concert harp with respect to their profile such as their level of learning of the instrument, or revovery from PRMD.

The fluocarbon strings' tension is higher than that of gut and nylon strings. We therefore hypothesized that the string's tension is a key parameter to understand the forearm muscle activity. However, the string tension is not sufficient to explain entirely our results. An assumption would be that the tactile properties of the strings would affect the harpist's perception and therefore the control developed during performance. Complementary studies will be required to understand the string material properties inducing such difference in the muscular coordination. Moreover, further work will approach the vibroacoustic side of this experiment to describe the evolution of the sound features with respect to the string materials.

A first limitation of the study concerns the number of harpists. Due to experimental constraints, only nine harpists were recruited, making it impossible to extrapolate the results to the entire population of harpists. Besides, a second limitation lies in the musical context of the experiment. Although a musical excerpt was investigated in addition to the isolated notes and the arpeggio sequences, only a global analysis was possible. Indeed, as several notes may be played simultaneously and that numerous ancillary gestures occurred, a fine analysis of muscular coordination with respect to sound producing and ancillary gestures remains a challenge. Finally, this study focused on finger and wrist flexor and extensor muscles in order to better understand the plucking action. Further work is required to investigate more closely the harpists' posture to get insight into the PRMDs located at their upper-back, neck and shoulders.

Conclusion

This study has experimentally described the evolution of forearm muscles activity during harp performance. The effect of string, playing dynamics and stringing material has been addressed. A noteworthy outcome is that harp playing requires a high recruitment of the fingers and wrist flexor (42 % of the MVC) and extensor muscles (29 % of the MVC). These findings have practical implications for injury prevention, highlighting the risk of playing-related musculoskeletal disorders (PRMDs) and emphasizing the importance of fingering and dynamics choices in minimizing muscle activation. Additionally, the study provides valuable insights into the precision-force trade-off influenced by different stringing materials, empowering harpists to make informed decisions regarding their instrument and musical control.

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Declaration of interest statement

The authors report there are no competing interests to declare.

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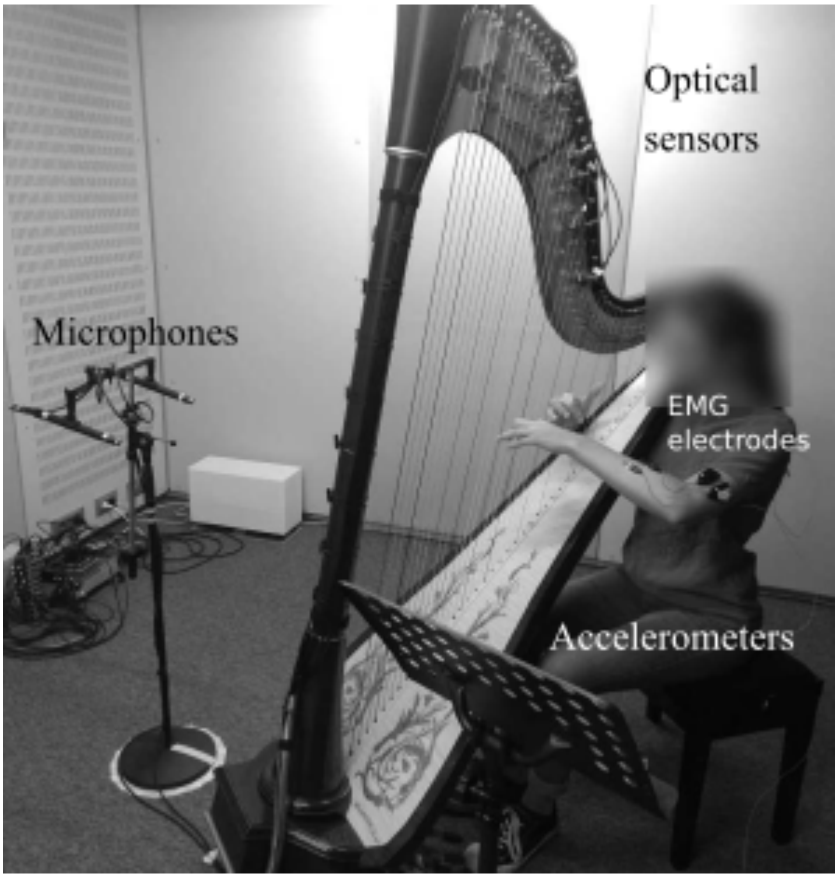
Tables:

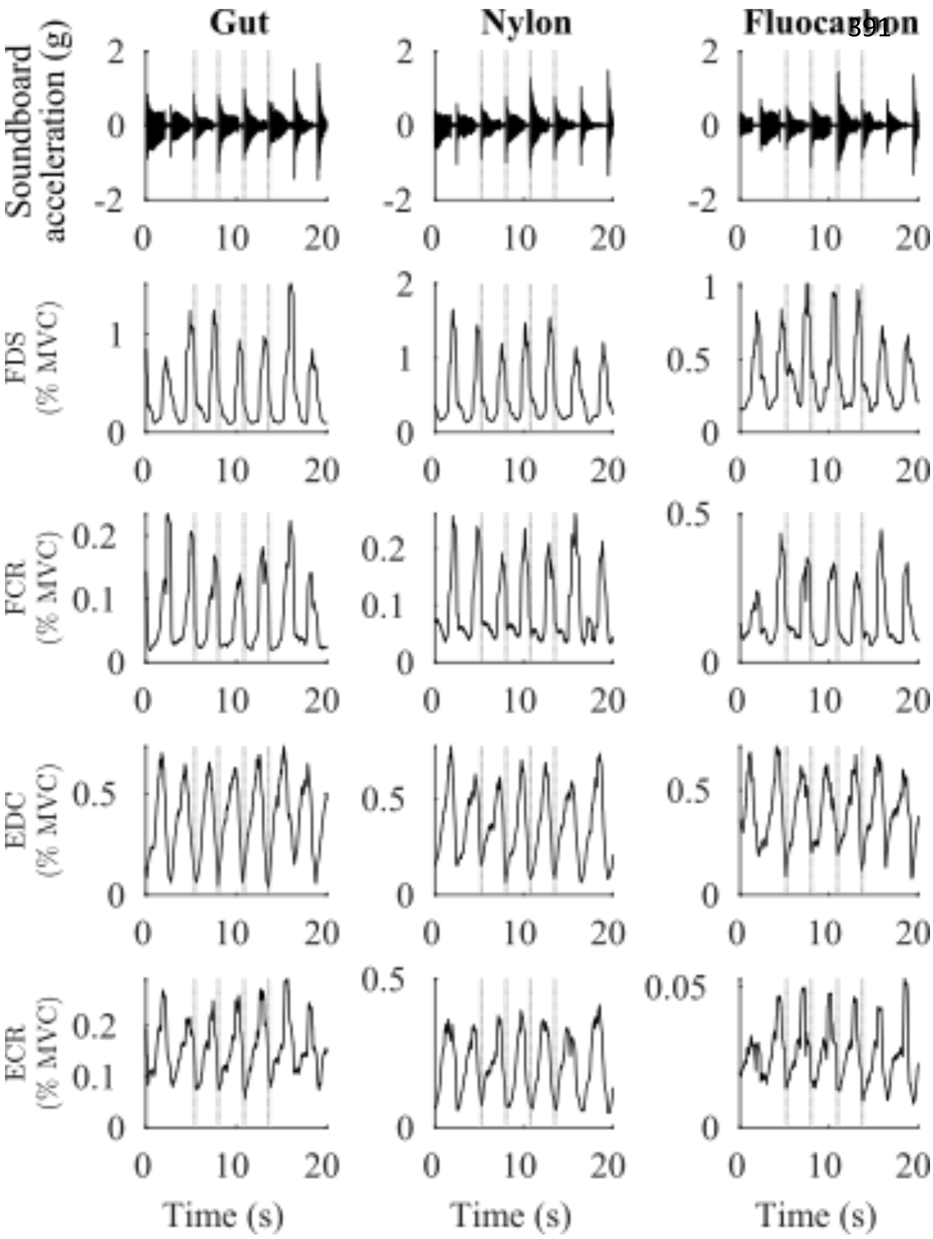
Table 1: Characteristics of studied strings

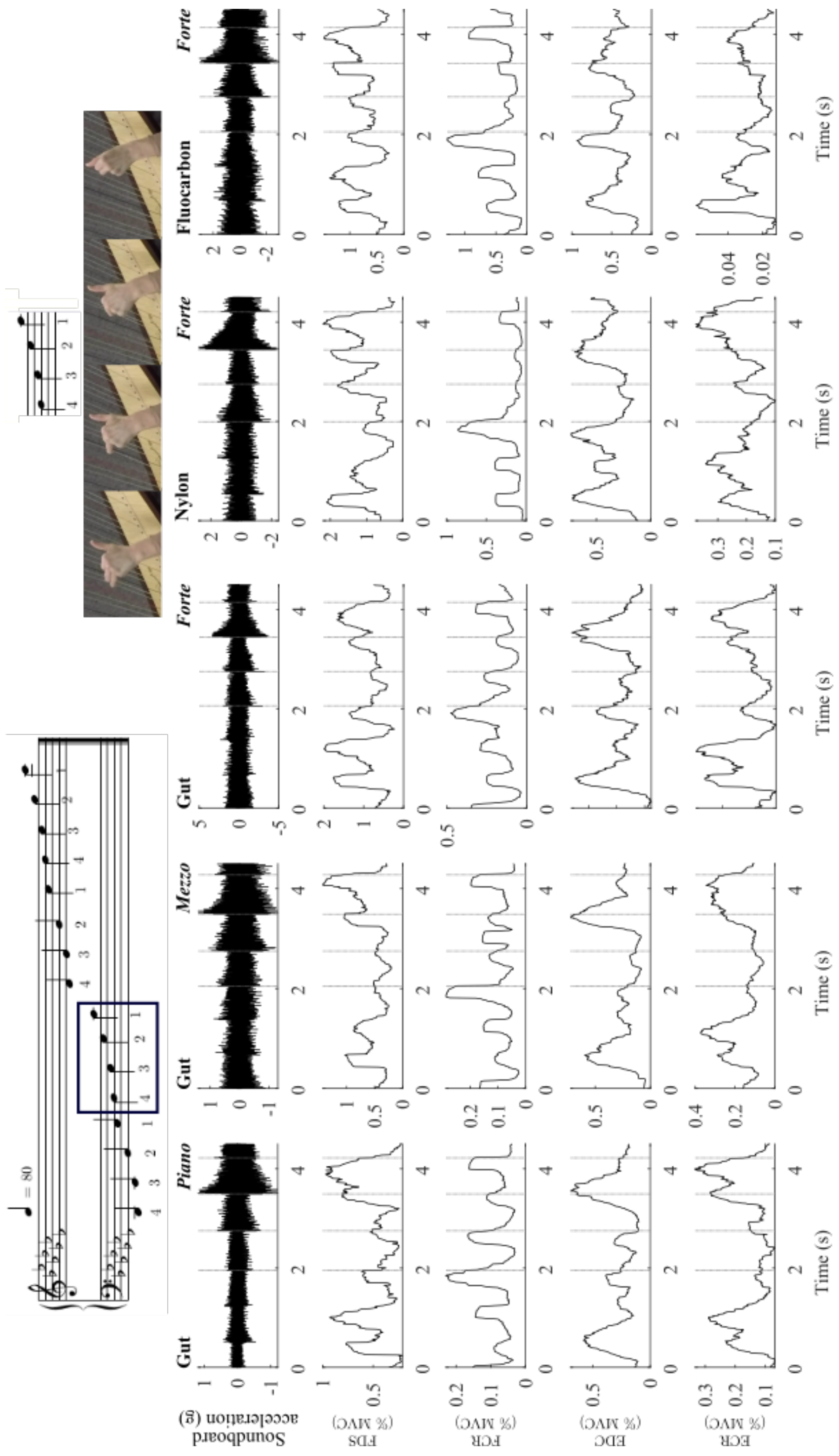
Note Number	D♭2(30)	E♭2 (29)	G♭2 (27)	C♭2 (24)
Frequency (Hz)	138.6	155.6	185	246.9
Length (cm)	97.5	90.7	76.8	58.8
Diameter (mm)				
Gut	1.93	1.85	1.65	1.39
Nylon	2.01	1.9	1.7	1.46
Fluocarbon	1.9	1.8	1.6	1.4
Tension (N)				
Gut	306	305	255	187
Nylon	262	277	227	161
Fluocarbon	364	372	298	235

Table 2: RMS levels (A) of each forearm muscle (FDS, FCR, EDC, ECR) activation for each stringing materials (Gut, Nylon, Fluocarbon) during the performance of the *Gimblette* (B. Andrès). The mean is computed on nine participants. The reported uncertainty represents a 95 % confidence interval.

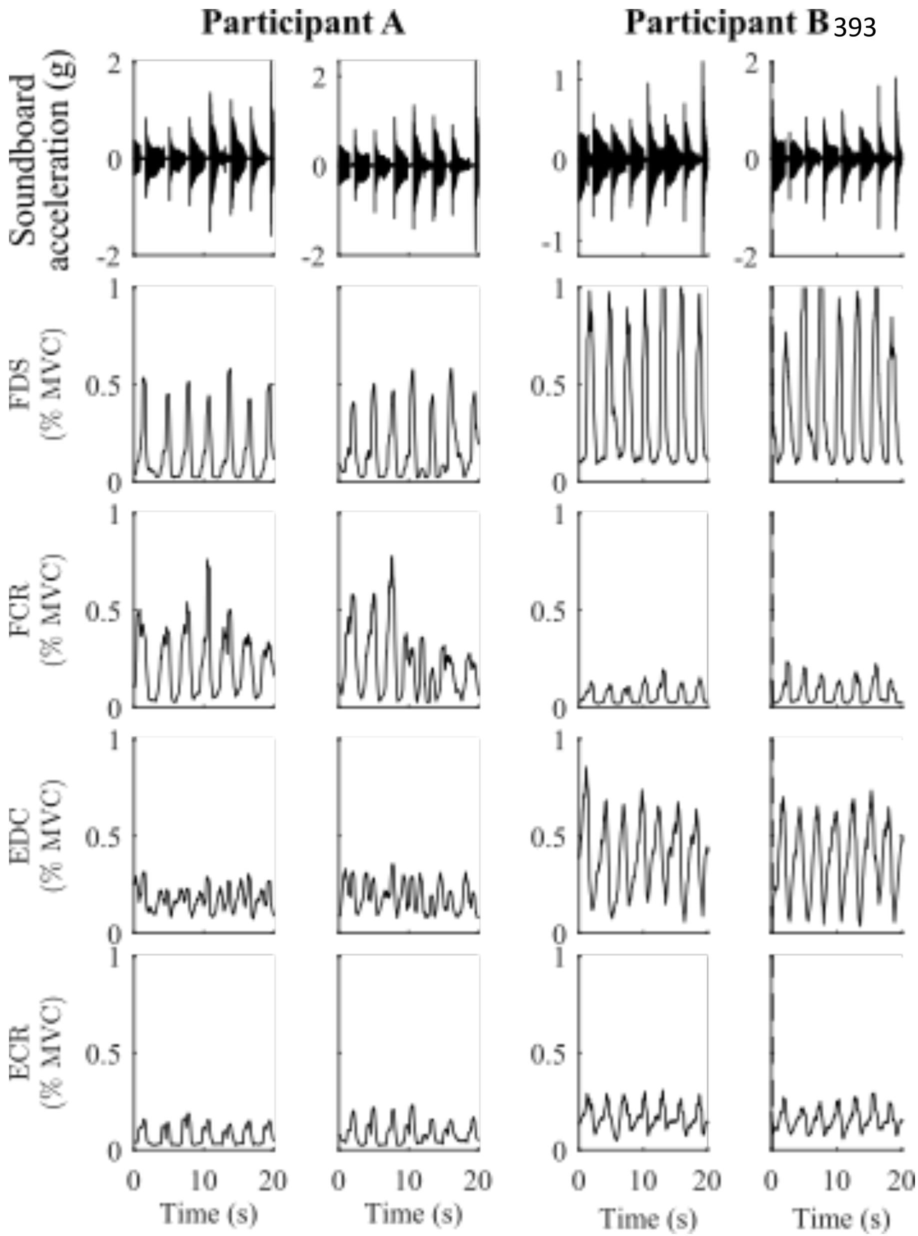
	Gut	Nylon	Fluocarbon
A^{FDS}	0.21 ± 0.09	0.38 ± 015	0.43 ± 0.21
A^{FCR}	0.16 ± 0.06	0.29 ± 0.13	0.41 ± 0.17
A^{EDC}	0.25 ± 0.10	0.21 ± 0.05	0.28 ± 0.03
A^{ECR}	0.15 ± 0.08	0.29 ± 0.11	0.19 ± 0.07

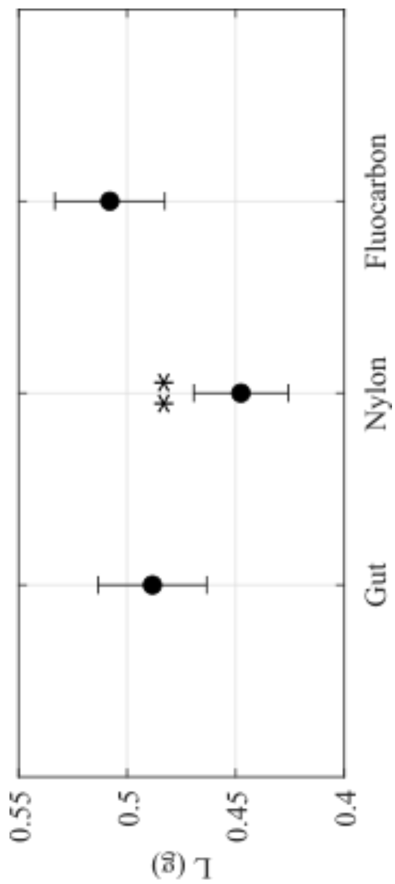

Optical
sensors
Microphones
EMG
electrodes
Accelerometers

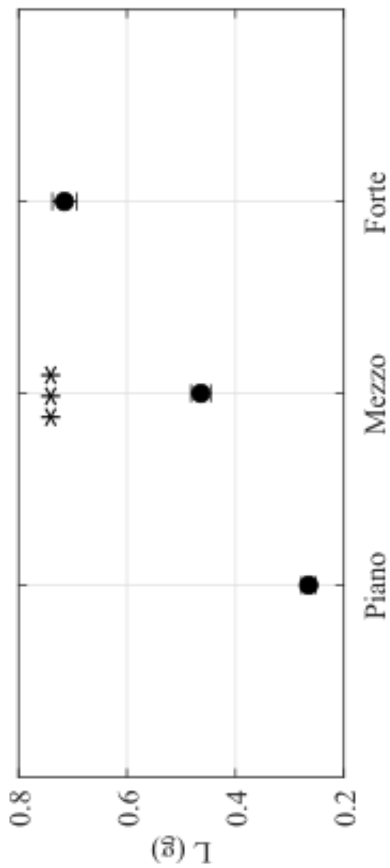

Gut
Nylon
Fluocarbon
Soundboard acceleration (g)
FDS (% MVC)
FCR (% MVC)
EDC (% MVC)
ECR (% MVC)
Time (s)
Time (s)
Time (s)



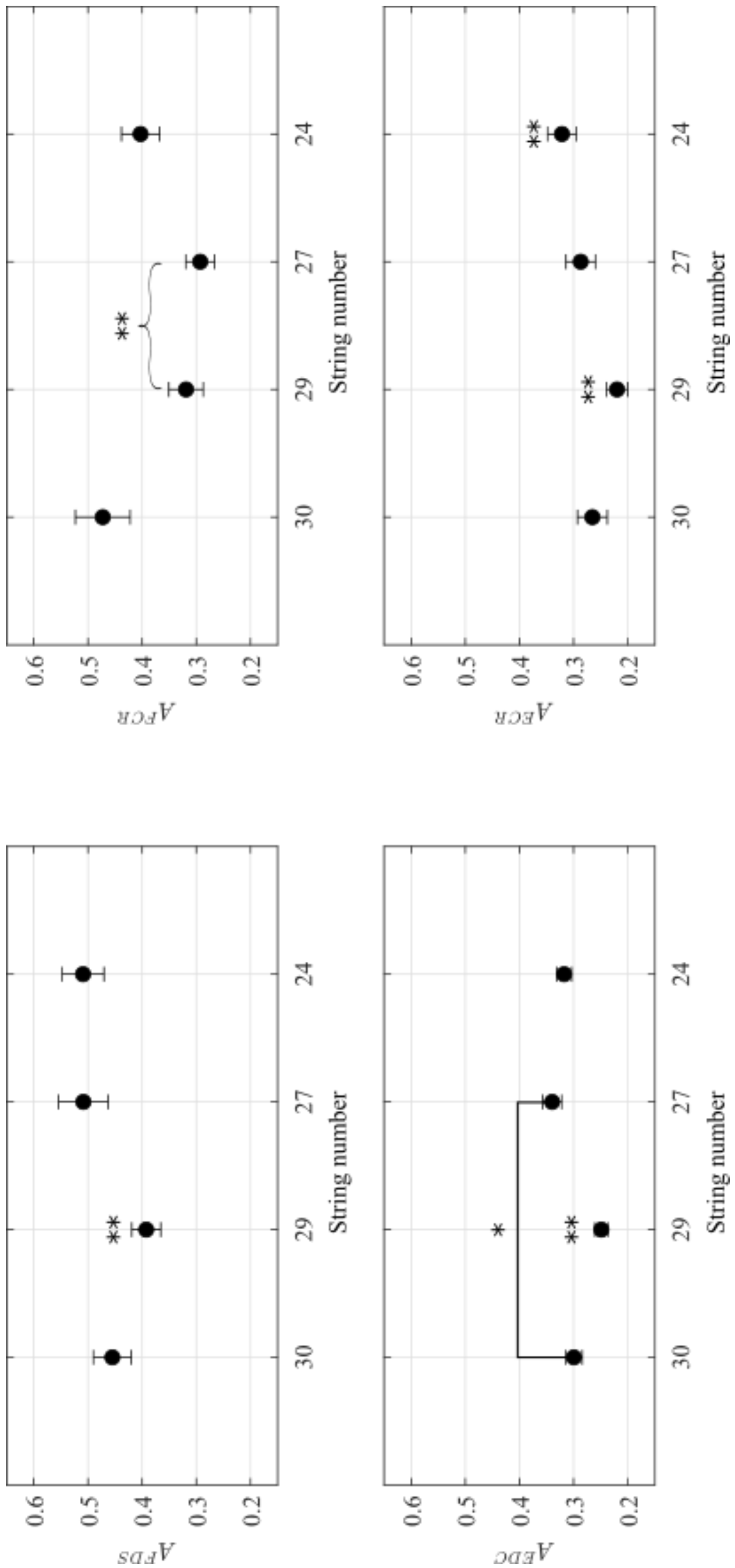
Soundboard acceleration (g)
FDS (% MVC)
FCR (% MVC)
EDC (% MVC)
ECR (% MVC)
Gut
Piano
Mezzo
Forte
Nylon
Fluocarbon
Time (s)

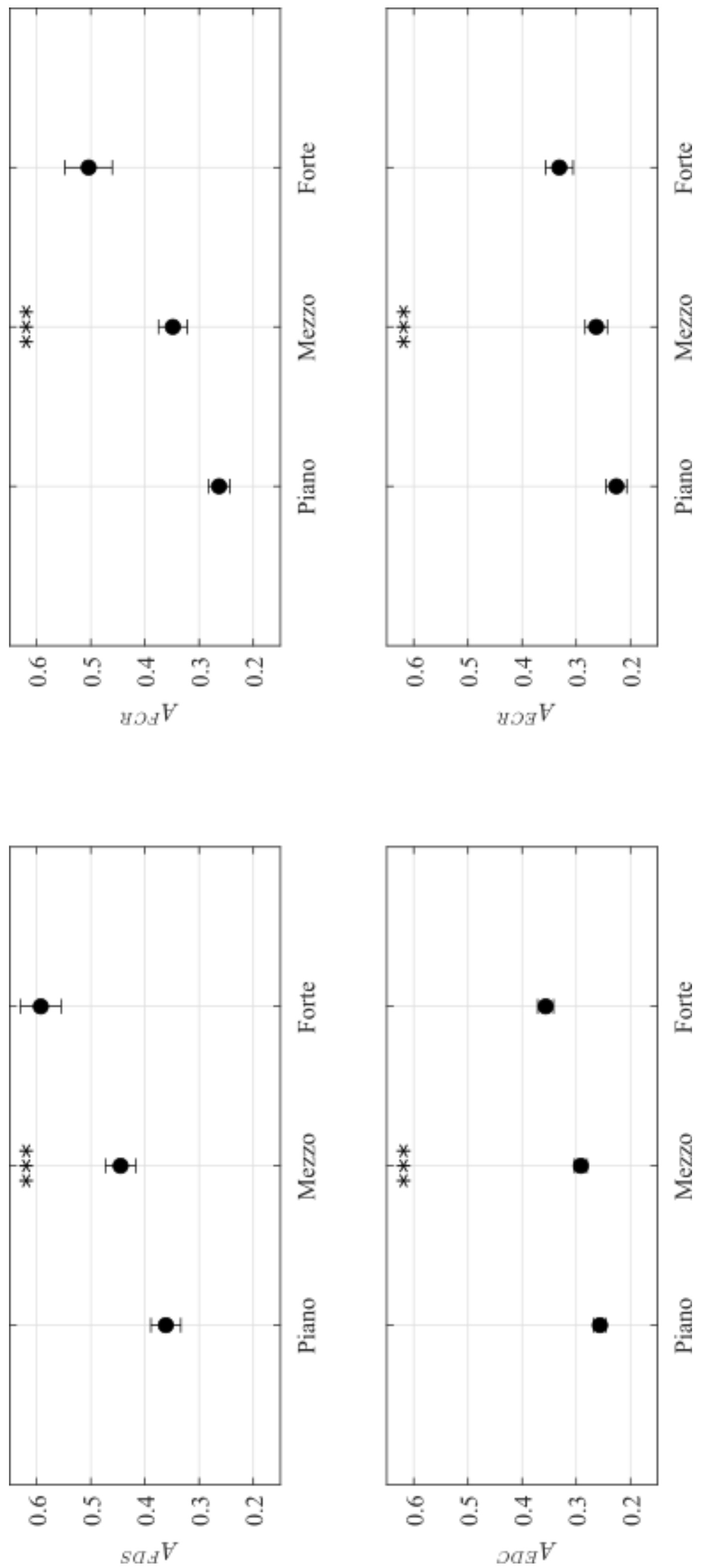

Participant A
Participant B
Soundboard acceleration (g)
FDS (% MVC)
FCR (% MVC)
EDC (% MVC)
ECR (% MVC)
Time (s)
393


L (g)
0.55
0.5
0.45
0.4
Gut
Nylon
Fluocarbon
**

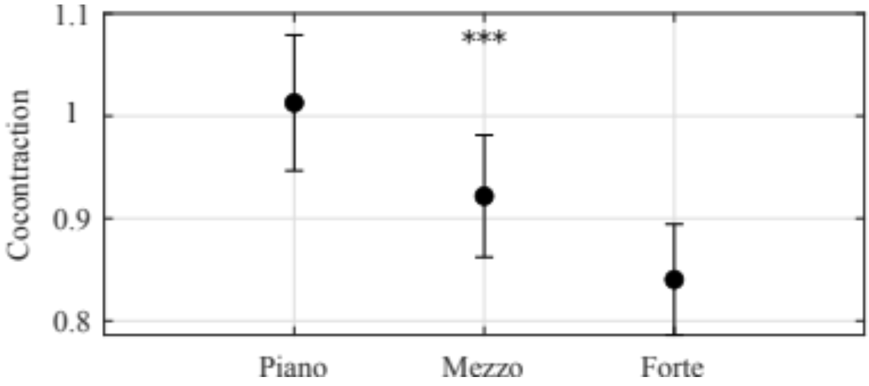

L (g)
0.8
0.6
0.4
0.2
Piano
Mezzo
Forte
***

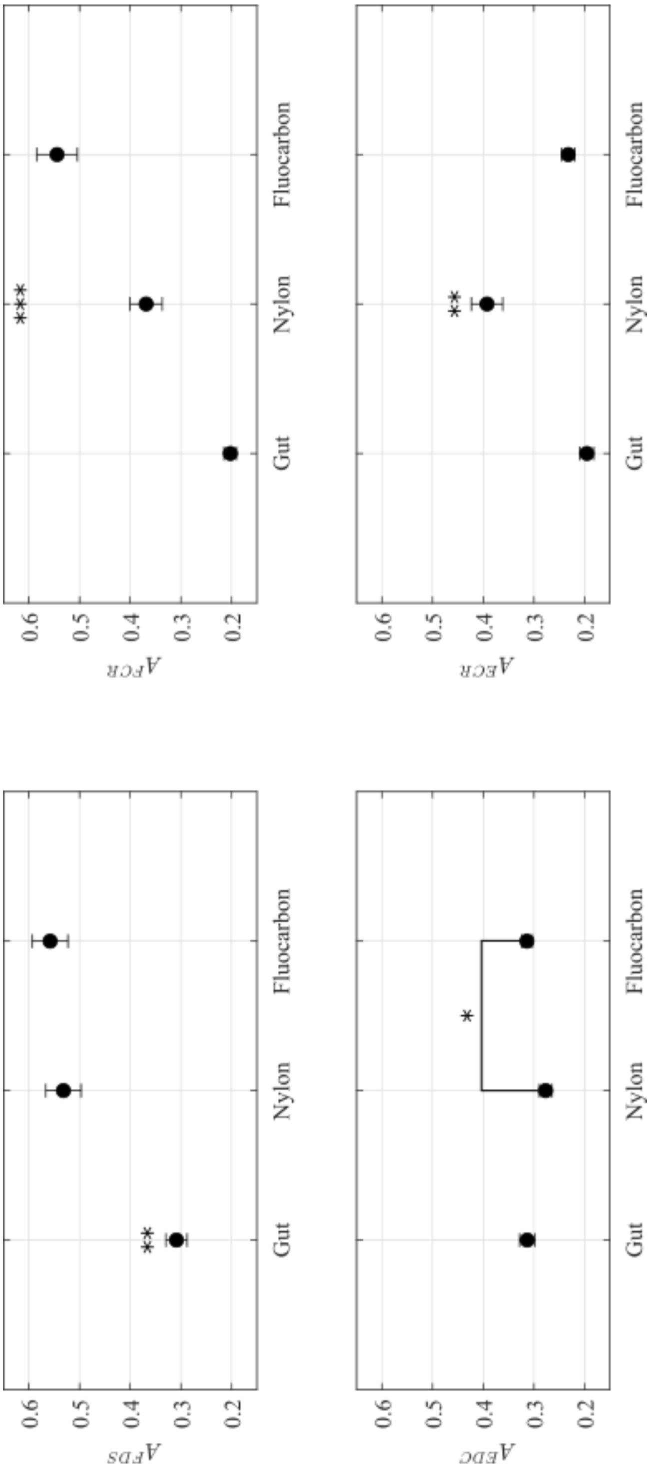
395





A_{FCR}
A_{ECR}
A_{FDS}
A_{EDC}
0.6
0.5
0.4
0.3
0.2
Piano
Mezzo
Forte
***


Cocontraction
1.1
1
0.9
0.8
***
Piano
Mezzo
Forte


A_FCR
A_ECR
A_FDS
A_EDC
0.6
0.5
0.4
0.3
0.2
Gut
Nylon
Fluocarbon
***
**
**
*

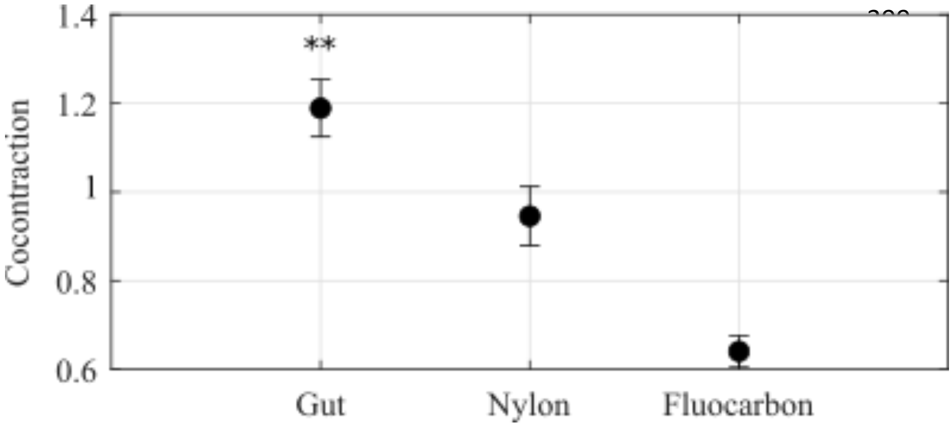

1.4
1.2
1
0.8
0.6
Cocontraction
**
Gut
Nylon
Fluocarbon

Figure Captions:

Figure 1: Experimental setup.

Figure 2: Forearm muscles activation signals (FDS, FCR, EDC, ECR) measured for one participant performing isolated notes on the three investigated stringing materials (gut, nylon, fluocarbon).

Figure 3: Forearm muscles activation signals (FDS, FCR, EDC, ECR) measured for one participant performing the arpeggio sequence with gut strings under the three dynamics (*Piano*, *Mezzoforte*, *Forte*), and with the three investigated stringing materials (gut, nylon, fluocarbon) under *Forte*.

Figure 4: Forearm muscles activation signals (FDS, FCR, EDC, ECR) measured for two participants performing isolated notes on gut strings twice.

Figure 5: RMS of the soundboard acceleration (L) for each investigated dynamics (*Piano*, *Mezzoforte*, *Forte*) and stringing material (gut, nylon, fluocarbon) during arpeggio performance. **, and *** indicate significant differences between the highlighted condition and all the other conditions, and between all the conditions, respectively. The reported uncertainty represents a 95 % confidence interval.

Figure 6: RMS level (A) of each forearm muscle activation (FDS, FCR, EDC, ECR) for each investigated string (30, 29, 27 and 24) during arpeggio performance. *, and ** indicate significant differences between two highlighted conditions, and between the highlighted condition and all the other conditions, respectively. The reported uncertainty represents a 95 % confidence interval.

Figure 7: RMS level (A) of each forearm muscle activation (FDS, FCR, EDC, ECR) for each investigated dynamics (*Piano*, *Mezzoforte*, *Forte*) during arpeggio performance. *** indicates

significant differences between all the conditions. The reported uncertainty represents a 95 % confidence interval.

Figure 8: Co-contraction estimated for each investigated dynamics (*Piano*, *Mezzoforte*, *Forte*) during arpeggio performance. *** indicates significant differences between all the conditions. The reported uncertainty represents a 95 % confidence interval.

Figure 9: RMS level (A) of each forearm muscle activation (FDS, FCR, EDC, ECR) for each investigated stringing material (gut, nylon, fluocarbon) during arpeggio performance. *, **, and *** indicate significant differences between two highlighted conditions, between the highlighted condition and all the other conditions, and between all the conditions, respectively. The reported uncertainty represents a 95 % confidence interval.

Figure 10: Co-contraction estimated for each investigated stringing material (gut, nylon, fluocarbon) during arpeggio performance. ** indicates significant differences between the highlighted condition and all the other conditions. The reported uncertainty represents a 95 % confidence interval.