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1 **Forearm muscles activity of harp players**

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8 **Forearm muscles activity of harp players**

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

25 **Keywords:** Concert harp; Electromyography; Biomechanics; Stringing

26 **Introduction**

27 Musical performance requires a wide range of cognitive, physiological and musical
28 skills such as instrument-specific motor skills and ability to repeat highly controlled
29 motions (Cohen & Bodner, 2019; Matei & Ginsborg, 2017). This physical commitment
30 makes musicians prone to “playing-related musculoskeletal disorders” (PRMD) (Rotter
31 et al., 2020; Zaza, 1998). Surveys have been conducted on professional musicians,
32 revealing that more than 75 % of them suffer from PRMD (Gasenzer et al., 2017; Kok

33 et al., 2016; Middlestadt & Fishbein, 1988). Muscular disorders include in particular
34 muscle-tendon unit overuse syndromes, and muscle imbalance movement impairment
35 syndromes (Caldron et al., 1986). Neuromuscular disorders include focal motor
36 dystonia, cervical radiculopathy, radial neuropathy and thoracic outlet syndrome
37 (Bejiani et al., 1996). As evidenced by the epidemiological study conducted by Martin
38 (2013), 74 % of harpists reveal pain, mainly located in the upper back, neck, and
39 shoulders. Martin (2013) assumed that harp strings tension is directly involved in the
40 musculoskeletal pain occurrence through the required muscular activation. This
41 assumption is reinforced by Moraes & Antunes (2012), underlining that an excessive
42 muscle tension is a factor of pain occurrence.

43 Musicians are looking for posture and techniques optimization to prevent
44 PRMDs by avoiding unnecessary efforts and muscle co-contractions (Bejiani et al.,
45 1996; Caldron et al., 1986). Training procedures are also explored to improve the
46 musician's force, and precision (Gorniak et al., 2019; Muramatsu et al., 2022). To
47 obtain quantitative insights, a few biomechanical studies have been recently published
48 (Blanco-Piñeiro et al., 2017; Goubault et al., 2021; Metcalf et al., 2014; Park et al.,
49 2019). Kinematics has mostly been interesting to address playing posture and ancillary
50 gestures (or accompanist gestures) (Wanderley et al., 2005). Further, exploring
51 biomechanical loads through inverse dynamic procedures is of great interest to approach
52 PRMDs. Investigating violin performance, Visentin & Shan (2003) showed that the
53 right shoulder loads vary according to the string played, whereas wrist and elbow loads
54 remain constant. Costalonga et al. (2019) developed an apparatus to study the forces
55 applied by the left-hand fingers while playing guitar. High frequency notes require a
56 higher range of forces on each string (2 to 10 N) than low frequency notes. Finally,
57 surface electromyography (EMG) is a common method to address musical performance

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

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

83 Under this framework, the present study aims at understanding how the harp
84 string properties and the playing dynamics affect the harp performance. Although the
85 PRMD related to harp performance are mainly located in the upper back, neck, and
86 shoulders, emphasis is placed on the forearm muscles activity to focus on the wrist and
87 finger motion, reflecting mostly the sound producing gestures. Our hypotheses are that
88 (1) flexor muscles are more activated than extensor muscles when playing harp; (2)
89 increased dynamics underlie increased muscular activation; and (3) the higher the
90 string's tension, the greater the muscular activation.
91 To address these hypotheses, an experiment has been carried out with harpists,
92 addressing the activation of four right forearm muscle sites with respect to various
93 strings, playing dynamics and stringing materials.

94 **Methodology**

95 ***Participants***

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

102 ***Concert harp***

103 Participants were asked to play on a concert harp (CAMAC Harps, Atlantide Prestige
104 model, see Figure 1). At each session, a new stringing was mounted on the concert harp
105 (CAMAC Harps, Atlantide Prestige model): gut, nylon, fluocarbon. Accounting for the
106 time needed to change and stabilize the stringing, each session took place on a different

107 day. The study was focused on a set of four strings. The physical characteristics of these
108 strings are provided in the Table 1.

109 ***Measurement protocol***

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

124 ***String vibration***

125 The bidimensional movement of the four studied strings (Table 1) was measured using
126 optical sensors (OPB815L OPTEK Technology Inc., Woking, United Kingdom,
127 sampling rate at 25600 Hz) fixed close to the instrument mechanism (Le Carrou et al.,
128 2014) (see Figure 1). These signals were used to point out each note onset, i.e. the
129 instant where each string starts oscillating after the plucking action.

130 ***Soundboard vibration***

131 The resulting soundboard vibration was simultaneously measured with two single-axis
132 accelerometers (PCB Piezotronics, Saint-Aubin, France, SN 352C65, 50 g pk, [0.5 –
133 10,000] Hz, sampling rate at 25600 Hz) located at the back of the soundboard.
134 Accelerometers were fixed between the strings 24 and 27, and between the strings 29
135 and 30. The first accelerometer was used to study the strings C_b1 and G_b1, while the
136 second was dedicated to the strings E_b2 and D_b2. Finally, the root-mean-squared (RMS)
137 acceleration level was computed over a 500 ms window from the note onset. This
138 variable is referred to as L.

139 *Muscular activation*

140 The plucking action consists mostly into a movement of fingers flexion associated to a
141 combination of wrist flexion/extension and abduction. Consequently EMG signals from
142 four forearm muscles (the flexor digitorum superficialis (FDS), the flexor carpi radialis
143 (FCR), the extensor digitorum communis (EDC), the extensor carpi radialis (ECR))
144 were collected using a wireless system (Delsys Trigno, Natick, MA, USA, sampling
145 rate at 1925 Hz) (see Figure 1). Electrodes were positioned after appropriate skin
146 preparation on the muscle bellies. First, recommendation proposed by (Cram, 2011)
147 were followed to identify the optimal electrode position. Then, to refine the electrode
148 position, muscle bellies were palpated while participants performed wrist and finger
149 isometric contractions. These tasks were separated into flexion and extension of the
150 wrist only and flexion and extension of the fingers only. This step was monitored to
151 verify the correct placement of the electrodes and to minimize cross-talk issues. Finally,
152 when seated, each participant realized maximal voluntary contraction (MVC) tasks to
153 evaluate the capacities of the four investigated muscle groups. MVC tasks for FDS and
154 EDC consisted into fingers maximal exertions in flexion and extension while keeping

155 the four long fingers together. MVC tasks for FCR and ECR consisted into wrist
156 maximal exertions in flexion and extension while keeping the fingers relaxed to avoid
157 extrinsic finger muscles contribution. Participants were verbally encouraged during each
158 MVC task. Each MVC task lasted five seconds, followed by a resting time of a minute,
159 and was repeated twice.

160 EMG signals passed through a bandpass filter and full-wave rectifier with zero
161 phase shift ([20--400] Hz; 4th order Butterworth). The associated RMS signals were
162 then calculated using a 500 ms moving window (Valero-Cuevas et al., 1998). For each
163 electrodes, the resulting signals were normalized by the maximal values measured
164 during the MVC tasks. Then, the RMS level of each forearm muscles activity during the
165 plucking action was computed over a 300 ms window before each note onset. The
166 window duration has been chosen based on the averaged plucking action duration
167 (Chadefaux et al., 2012). This variable is referred to as A^{emg} where $emg = \{EDC, ECR,$
168 $FDS, FCR\}$.

169 ***Muscular co-contraction***

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

174 ***Statistics***

175 In order to describe the forearm muscles activity during a concert harp performance,
176 each previously defined variable was investigated regarding the played strings, the
177 playing dynamics, and the stringing material. Given the sample size (nine participants),
178 the nonparametric Friedman's test with repeated measures were carried out to highlight
179 the effect of the playing dynamics and the stringing material on the forearm muscles

180 activity. When a significant effect was observed ($p < 0.05$), a multiple comparison post-
181 hoc test (Nemenyi test) was carried out to determine the conditions leading to
182 significant differences.

183 **Results**

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

187 *Muscular activation patterns*

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

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

200 Regarding further arpeggio sequence, the four forearm muscle sites investigated
201 presented specific but repeated activation signals accross the dynamics and the stringing
202 materials (see Figure 3). Unlike the isolated notes sequence, no resting period occurred

203 in the arpeggio sequence. Indeed, to play a group of four consecutive notes, the hand
204 was fixed and the fingertips were pressed on the strings. As a result, the muscular
205 activation never decreased as for playing isolated notes, and signals were less
206 straightforward to relate to the score. Accordingly to the isolated notes sequence, the
207 note onset occurred during the decreasing phase of the activation pattern.

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

215 Investigating further the averaged activation level of FDS, FCR, EDC and ECR
216 while playing harp, the flexor muscles activation was outlined higher than the extensor
217 muscles activation. In a lesser extent, finger muscles' activation was slightly higher than
218 the wrist muscles activation. Indeed, performing isolated notes A^{FDS} and A^{FCR} reached
219 about 44 % and 37 % of the MVC, while A^{EDC} and A^{ECR} reached about 23 % and 20 %
220 of the MVC. Similarly, performing arpeggio, A^{FDS} and A^{FCR} reached about 47 % and
221 37 % of the MVC while A^{EDC} and A^{ECR} reached about 30 % and 27 % of the MVC.

222 ***Soundboard vibration***

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

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

230 ***String effect***

231 Forearm muscle activation was significantly affected by the four investigated strings
232 (FDS: $\chi^2 = 128$, $df = 3$, $p < 0.01$; FCR: $\chi^2 = 360$, $df = 3$, $p < 0.01$; EDC: $\chi^2 = 192$, $df = 3$,
233 $p < 0.01$; ECR: $\chi^2 = 349$, $df = 3$, $p < 0.01$). In particular, Figure 6 reveals a significantly
234 lower forearm muscle activation when plucking the string 29 regardless of the muscle.
235 The RMS level of FDS was increased when plucking the strings 27 and 24 compared to
236 the strings 30 and 29. On the opposite, the RMS level of FCR was measured higher
237 when plucking the strings 30 and 24 than the strings 29 and 27. Besides, the activation
238 of the extensor muscles appeared slightly higher when plucking the strings 27 and 24
239 than the strings 30 and 29.

240 ***Dynamics effect***

241 Figure 7 highlights significant differences between the RMS level of the four forearm
242 muscles activation with respect to the dynamics conditions (FDS: $\chi^2 = 860$, $df = 2$,
243 $p < 0.01$; FCR: $\chi^2 = 851$, $df = 2$, $p < 0.01$; EDC: $\chi^2 = 569$, $df = 2$, $p < 0.01$; ECR:
244 $\chi^2 = 108$, $df = 2$, $p < 0.01$). Regardless the forearm muscle, the RMS level of muscular
245 activation significantly increased with the dynamics condition. More specifically, $A^{(FCR,$
246 $FDS)}$ increased more rapidly than $A^{(ECR, EDC)}$ with respect to the playing dynamics
247 (increase of 76 % versus 42 % in average from the *Piano* to *Mezzoforte*).

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

250 *Stringing material effect*

251 Figure 9 shows significant differences between Nylon, Gut and Fluocarbon strings
252 (FDS: $\chi^2 = 262$, $df = 2$, $p < 0.01$; FCR: $\chi^2 = 353$, $df = 2$, $p < 0.01$; EDC: $\chi^2 = 59$, $df = 2$,
253 $p < 0.01$; ECR: $\chi^2 = 113$, $df = 2$, $p < 0.01$). $A^{(FCR, FDS)}$ reached values from about 25 %
254 and 55 % of the MVC. The RMS level of extensor muscles activation reached about
255 23 % of the MVC regardless the stringing materials. Aside from an activation of ECR
256 reaching about 40 % of the MVC when playing Nylon strings, the same orders of
257 magnitude were observed when playing arpeggio. The RMS level of flexor muscles
258 activation was increased when playing Nylon and Fluocarbon strings compared to Gut
259 strings. Regarding the RMS level of extensor muscles activation, Nylon strings induced
260 a lower activation of EDC and a higher activation of ECR with respect to Gut strings
261 and Fluocarbon strings.

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

267 *Musical excerpt performance*

268 The analysis of the *Gimblette* performance outlined that the RMS level of flexor
269 muscles was increased from Gut strings to Nylon strings and Fluocarbon strings (see
270 Table 2). Aside from Nylon strings that induced a slight deviation ($A^{EDC}(Nylon) <$
271 $A^{EDC}(Gut, Fluocarbon)$ and $A^{ECR}(Nylon) > A^{ECR}(Gut, Fluocarbon)$), the RMS level of
272 the extensor muscles presented similar values when playing with Gut and Fluocarbon
273 strings.

274 **Discussion**

275 The muscular activation patterns revealed an important involvement of FDS, FCR, EDC
276 and ECR during harp plucking (about 47 %, 37 %, 30 % and 27 %, respectively). As
277 expected according to the harp plucking gesture, flexor muscles were more activated
278 than extensor muscles. As already observed by (Itoigawa, 2019) during guitar
279 performance, the note onset occurred during the muscular activation decrease rather
280 than at its maximal value. This result is most likely explained by the plucking action
281 description. Indeed, as previously outlined, the string is first pulled from its resting
282 position before slipping over the finger surface up to the note onset (Chadefaux et al.,
283 2012).

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

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

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

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

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

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

345 The fluocarbon strings' tension is higher than that of gut and nylon strings. We
346 therefore hypothesized that the string's tension is a key parameter to understand the
347 forearm muscle activity. However, the string tension is not sufficient to explain entirely
348 our results. An assumption would be that the tactile properties of the strings would

349 affect the harpist's perception and therefore the control developed during performance.
350 Complementary studies will be required to understand the string material properties
351 inducing such difference in the muscular coordination. Moreover, further work will
352 approach the vibroacoustic side of this experiment to describe the evolution of the
353 sound features with respect to the string materials.

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

365 **Conclusion**

366 This study has experimentally described the evolution of forearm muscles activity
367 during harp performance. The effect of string, playing dynamics and stringing material
368 has been addressed. A noteworthy outcome is that harp playing requires a high
369 recruitment of the fingers and wrist flexor (42 % of the MVC) and extensor muscles
370 (29 % of the MVC). These findings have practical implications for injury prevention,
371 highlighting the risk of playing-related musculoskeletal disorders (PRMDs) and
372 emphasizing the importance of fingering and dynamics choices in minimizing muscle
373 activation. Additionally, the study provides valuable insights into the precision-force

374 trade-off influenced by different stringing materials, empowering harpists to make
375 informed decisions regarding their instrument and musical control.

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379 **Declaration of interest statement**

380 The authors report there are no competing interests to declare.

- Baeyens, J., Serrien, B., Goossens, M., Veekmans, K., Baeyens, R., Daems, W., Cattrysse, E., & Clijsen, R. (2020). Effects of rehearsal time and repertoire speed on extensor carpi radialis EMG in conservatory piano students. *Medical Problems of Performing Artists*, 35(2), 81–88.
- Bejiani, F., Kaye, G., & Benham, M. (1996). Musculoskeletal and neuromuscular conditions of instrumental musicians. *Archives of Physical Medicine and Rehabilitation*, 77(4), 406–413. [https://doi.org/10.1016/S0003-9993\(96\)90093-3](https://doi.org/10.1016/S0003-9993(96)90093-3)
- Blanco-Piñeiro, P., Díaz-Pereira, M. P., & Martínez, A. (2017). Musicians, postural quality and musculoskeletal health: A literature's review. *Journal of Bodywork and Movement Therapies*, 21(1), 157–172. <https://doi.org/10.1016/j.jbmt.2016.06.018>
- Caldron, P., Calabrese, L., Clough, J., Lederman, R., Williams, G., & Leatherman, J. (1986). MA survey of musculoskeletal problems encountered in high-level musicians. *Medical Problems of Performing Artists*, 1(4), 136–139.
- Cattarello, P., Merletti, R., & Petracca, F. (2017). Analysis of high-density surface EMG and finger pressure in the left forearm of violin players: A feasibility study. *Medical Problems of Performing Artists*, 32(3), 139–151. <https://doi.org/10.21091/mppa.2017.3023>
- Chadefaux, D. (2012). *Interaction Musicien/Instrument: Le cas de la harpe de concert*. Université Pierre et marie Curie.
- Chadefaux, D., Le Carrou, J.-L., Fabre, B., & Daudet, L. (2012). Experimentally based description of harp plucking. *Journal of The Acoustical Society of America*, 131(1), 844–855.
- Chadefaux, D., Le Carrou, J.-L., Fabre, B., & Daudet, L. (2014). *Sound, music, and motion, lecture notes in computer science* (Vol. 8907, pp. 3–19). Springer.

- Chadefaux, D., Le Carrou, J.-L., Wanderley, M.-M., Fabre, B., & Daudet, L. (2013). Gestural strategies in the harp performance. *Acta Acustica United With Acustica*, 99, 986–996.
- Chong, H. J., Kim, S. J., & Yoo, G. E. (2015). Differential effects of type of keyboard playing task and tempo on surface EMG amplitudes of forearm muscles. *Frontiers in Psychology*, 6(20).
- Cohen, S., & Bodner, E. (2019). Music performance skills: A two-pronged approach – facilitating optimal music performance and reducing music performance anxiety. *Psychology of Music*, 47(4), 521–538.
<https://doi.org/10.1177/0305735618765349>
- Costalonga, L. L., Pimenta, M. S., & Miranda, E. R. (2019). Understanding biomechanical constraints for modelling expressive performance: A guitar case study. *Journal of New Music Research*, 48(4), 331–351.
<https://doi.org/10.1080/09298215.2019.1643892>
- Cram, J. R. (2011). *Cram's Introduction to Surface Electromyography* (2nd ed.). Eleanor Criswell, EdD.
- Degrave, V., Verdugo, F., Pelletier, J., Traube, C., & Begon, M. (2020). Time history of upper-limb muscle activity during isolated piano keystrokes. *Journal of Electromyography and Kinesiology*, 54(102459).
- Duprey, S., Michaud, B., & Begon, M. (2017). Muscular activity variations of the right bowing arm of the violin player. *Computer Methods in Biomechanics and Biomedical Engineering*, 20(sup1), S71–S72.
<https://doi.org/10.1080/10255842.2017.1382866>
- Gasenzer, E.-R., Klumpp, M.-J., Pieper, D., & Neugebauer, E.-A. (2017). The prevalence of chronic pain in orchestra musicians. *German Medical Science*, 15.
- Gorniak, S. L., Collins, E. D., Goldie Staines, K., Brooks, F. A., & Young, R. V. (2019). The Impact of Musical Training on Hand Biomechanics in String Musicians. *HAND*, 14(6), 823–829. <https://doi.org/10.1177/1558944718772388>

- Goubault, E., Verdugo, F., Pelletier, J., Traube, C., Begon, M., & Dal Maso, F. (2021). Exhausting repetitive piano tasks lead to local forearm manifestation of muscle fatigue and negatively affect musical parameters. *Scientific Reports*, *11*(8117), 3881–3888.
- Itoigawa, R. (2019). Proposal of a human-instrument interaction model and its basic examination using electromyogram. *International Symposium on Musical Acoustics (ISMA)*, Detmold, Germany.
- Kok, L. M., Huisstede, B. M. A., Voorn, V. M. A., Schoones, J. W., & Nelissen, R. G. H. H. (2016). The occurrence of musculoskeletal complaints among professional musicians: A systematic review. *International Archives of Occupational and Environmental Health*, *89*(3), 373–396. <https://doi.org/10.1007/s00420-015-1090-6>
- Le Carrou, J.-L., Chadeaux, D., Seydoux, L., & Fabre, B. (2014). A low-cost high-precision measurement method of string motion. *Journal of Sound and Vibration*, *333*, 3881–3888.
- Mann, S., Panduro, M. B., Paarup, H. M., Brandt, L., & Sogaard, K. (2021). Surface electromyography of forearm and shoulder muscles during violin playing. *Journal of Electromyography and Kinesiology*, *56*, 102491. <https://doi.org/10.1016/j.jelekin.2020.102491>
- Martin, R. (2013). Tension/Détente de la posture du harpiste en Europe occidentale. *Médecine Des Arts*, *74*, 10–16.
- Matei, R., & Ginsborg, J. (2017). Music performance anxiety in classical musicians – what we know about what works. *BJPsych. International*, *14*(2), 33–35. <https://doi.org/10.1192/S2056474000001744>
- Metcalf, C.-D., Irvine, I.-A., Sims, J.-L., Wang, Y.-L., Su, A.-W.-Y., & Norris, D.-O. (2014). Complex hand dexterity: A review of biomechanical methods for measuring musical performance. *Frontiers in Psychology*, *5*, 414. <https://doi.org/10.3389/fpsyg.2014.00414>

- Middlestadt, S.-E., & Fishbein, M. (1988). Health and occupational correlates of perceived occupational stress in symphony orchestra musicians. *J. Occup Med*, *30*(9), 687—692.
- Muramatsu, K., Oku, T., & Furuya, S. (2022). The plyometric activity as a conditioning to enhance strength and precision of the finger movements in pianists. *Scientific Reports*, *12*(1), 22267. <https://doi.org/10.1038/s41598-022-26025-0>
- Oikawa, N., Tsubota, S., Chikenji, T., Chin, G., & Aoki, M. (2011). Wrist Positioning and Muscle Activities in the Wrist Extensor and Flexor during Piano Playing. *Hong Kong Journal of Occupational Therapy*, *21*(1), 41–46. <https://doi.org/10.1016/j.hkjot.2011.06.002>
- Overton, M., Du Plessis, H., & Sole, G. (2018). Electromyography of neck and shoulder muscles in instrumental musicians with musculoskeletal pain compared to asymptomatic controls: A systematic review and meta-analysis. *Musculoskeletal Science and Practice*, *36*, 32–42. <https://doi.org/10.1016/j.msksp.2018.04.001>
- Park, S.-H., Ihm, S.-Y., Nasridinov, A., & Park, Y.-H. (2019). A feasibility test on preventing PRMDs based on deep learning. *AAAI*.
- Rotter, G., Noeres, K., Fernholz, I., Willich, S.-N., Schmidt, A., & Berghöfer, A. (2020). Musculoskeletal disorders and complaints in professional musicians: A systematic review of prevalence, risk factors, and clinical treatment effects. *International Archives of Occupational and Environmental Health*, *93*(2), 149–187. <https://doi.org/10.1007/s00420-019-01467-8>
- Russo, A., Aranceta-Garza, A., D’Emanuele, S., & Merletti, R. (2019). HDsEMG activity of the lumbar erector spinae in violin players. *Medical Problems of Performing Artists*, *34*(4), 205–214.
- Steinmetz, A., Claus, A., Hodges, P. W., & Jull, G. A. (2016). Neck muscle function in violinists/violists with and without neck pain. *Clinical Rheumatology*, *35*(4), 1045–1051. <https://doi.org/10.1007/s10067-015-3000-4>

- Valero-Cuevas, F.-J., Zajac, F.-E., & Burgar, C.-G. (1998). Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. *Journal of Biomechanics*, *31*, 693–703.
- Visentin, P., & Shan, G. (2003). The kinetic characteristics of the bow arm during violin performance: An examination of internal loads as a function of tempo. *Medical Problems of Performing Artists*, *18*(3), 91–97.
- Wanderley, M.-M., Vines, B., Middleton, N., & McKay, C. (2005). The musical significance of clarinetists' ancillary gestures: An exploration of the field. *Journal of New Music Research*, *34*(1), 97–113.
- Zaza, C. (1998). Playing-related musculoskeletal disorders in musicians: A systematic review of incidence and prevalence. *Canadian Medical Association Journal*, *158*(8), 1019–1025.

382 **Tables:**

383 Table 1: Characteristics of studied strings

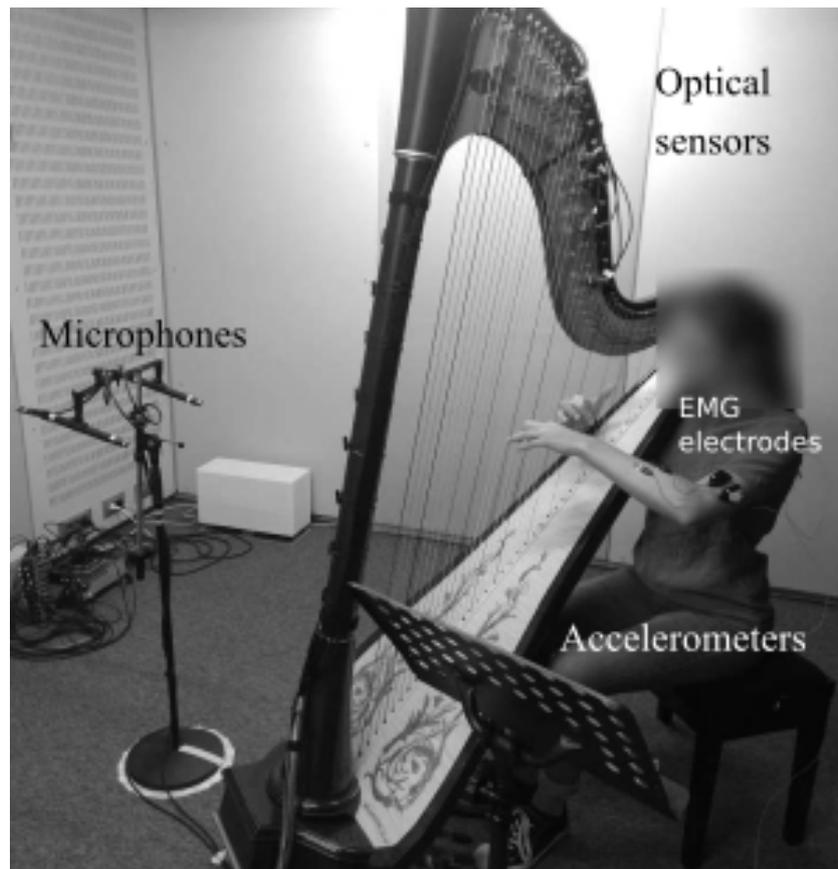
Note Number	Db2(30)	Eb2 (29)	Gb2 (27)	Cb2 (24)
Frequency (Hz)	138.6	155.6	185	246.9
Length (cm)	97.5	90.7	76.8	58.8
Diameter (mm)				
<i>Gut</i>	1.93	1.85	1.65	1.39
<i>Nylon</i>	2.01	1.9	1.7	1.46
<i>Fluocarbon</i>	1.9	1.8	1.6	1.4
Tension (N)				
<i>Gut</i>	306	305	255	187
<i>Nylon</i>	262	277	227	161
<i>Fluocarbon</i>	364	372	298	235

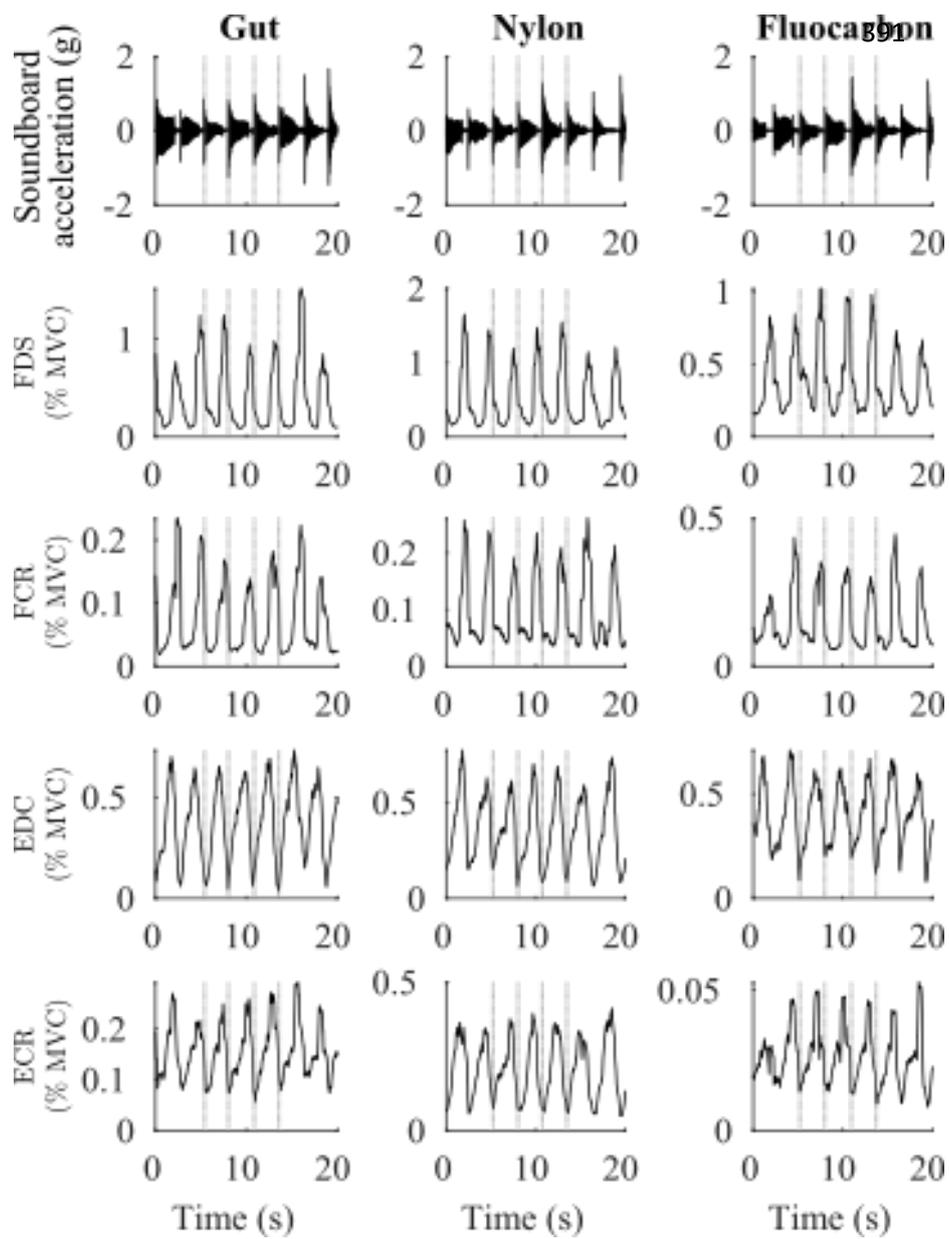
384

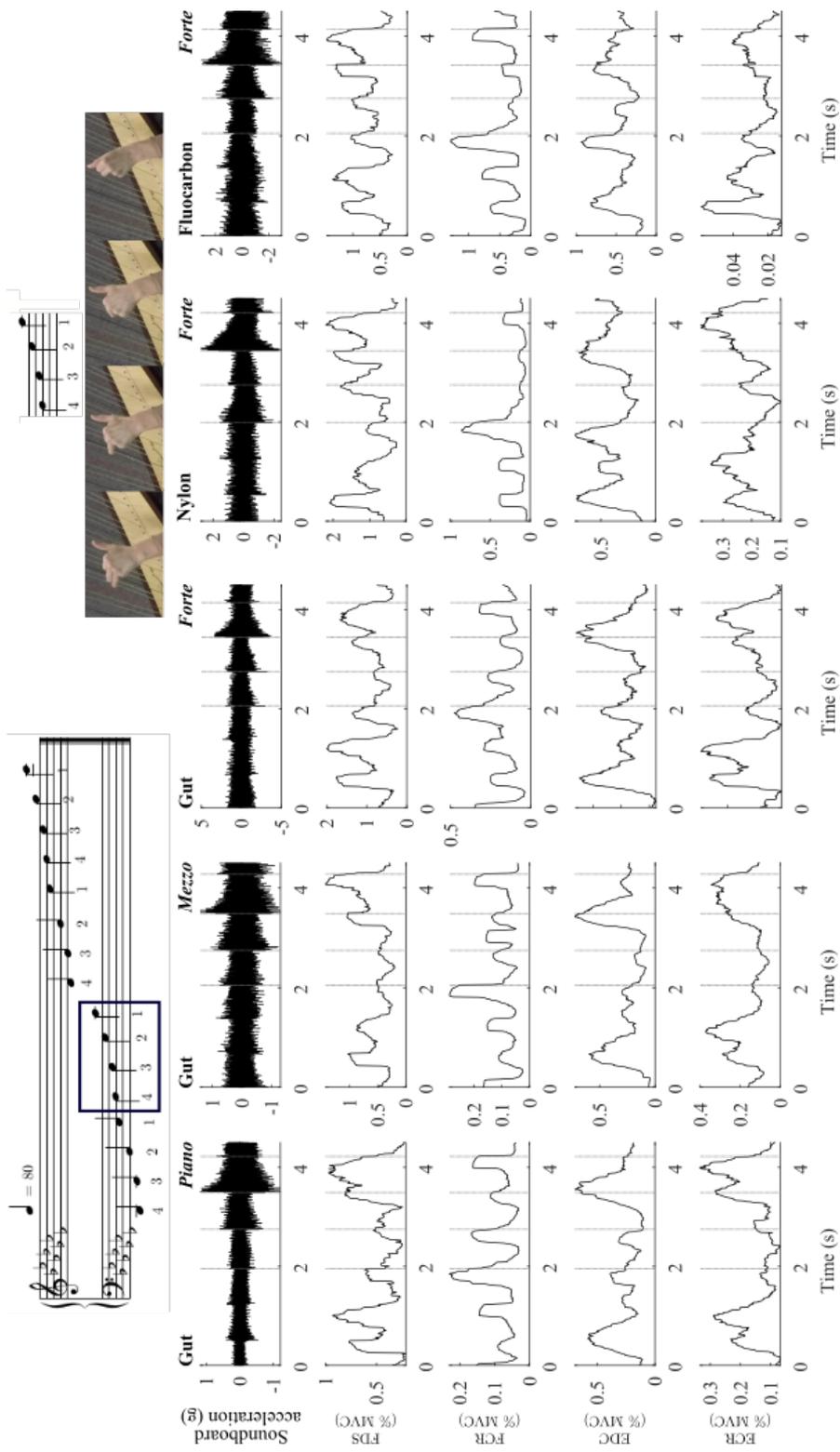
385 Table 2: RMS levels (A) of each forearm muscle (FDS, FCR, EDC, ECR) activation for each
 386 stringing materials (Gut, Nylon, Fluocarbon) during the performance of the *Gimblette* (B.
 387 Andrès). The mean is computed on nine participants. The reported uncertainty represents a 95 %
 388 confidence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

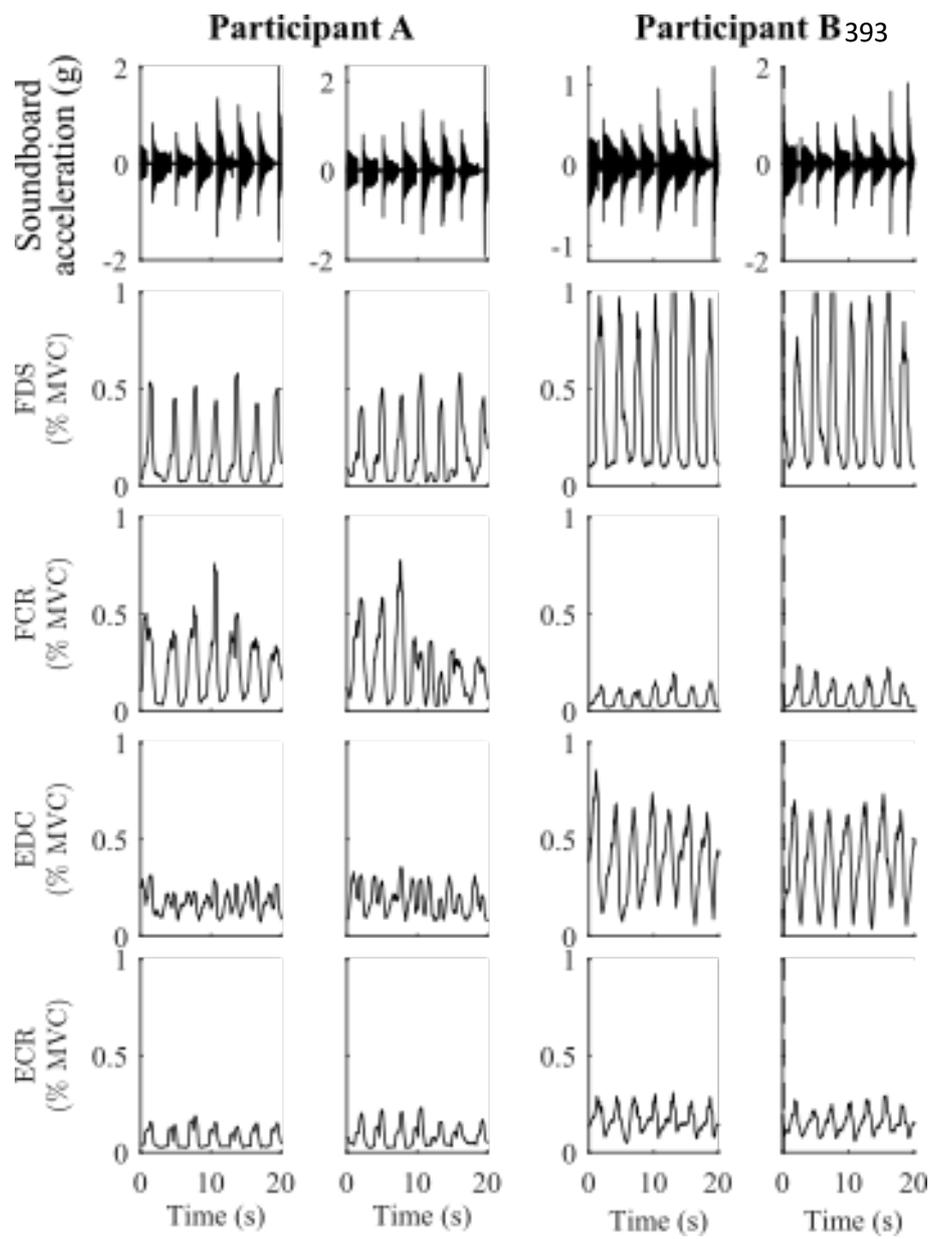
	Gut	Nylon	Fluocarbon
A^{FDS}	0.21 ± 0.09	0.38 ± 0.15	0.43 ± 0.21
A^{FCR}	0.16 ± 0.06	0.29 ± 0.13	0.41 ± 0.17
A^{EDC}	0.25 ± 0.10	0.21 ± 0.05	0.28 ± 0.03
A^{ECR}	0.15 ± 0.08	0.29 ± 0.11	0.19 ± 0.07

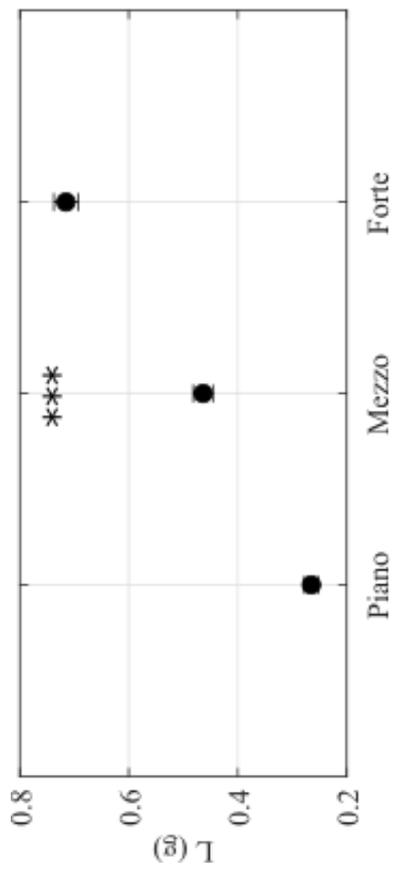
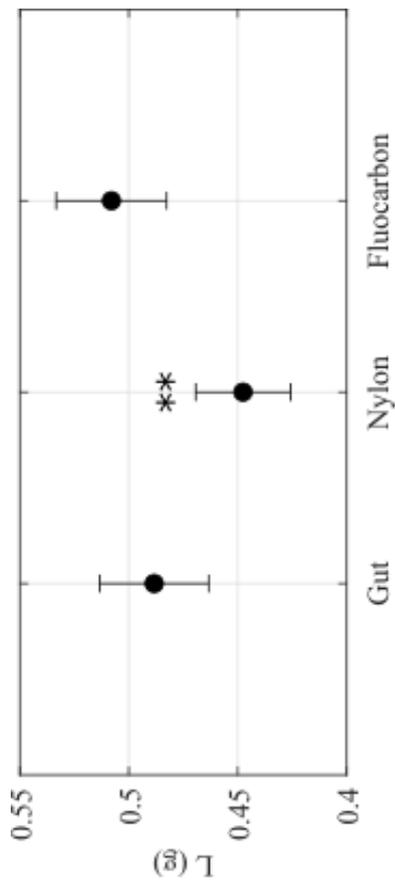
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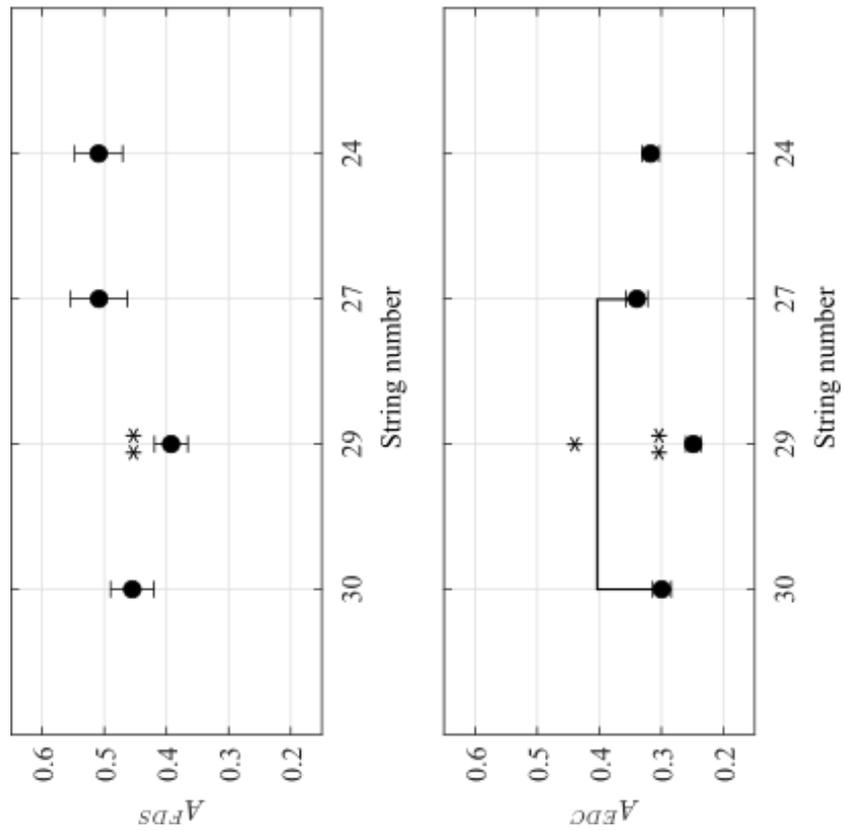
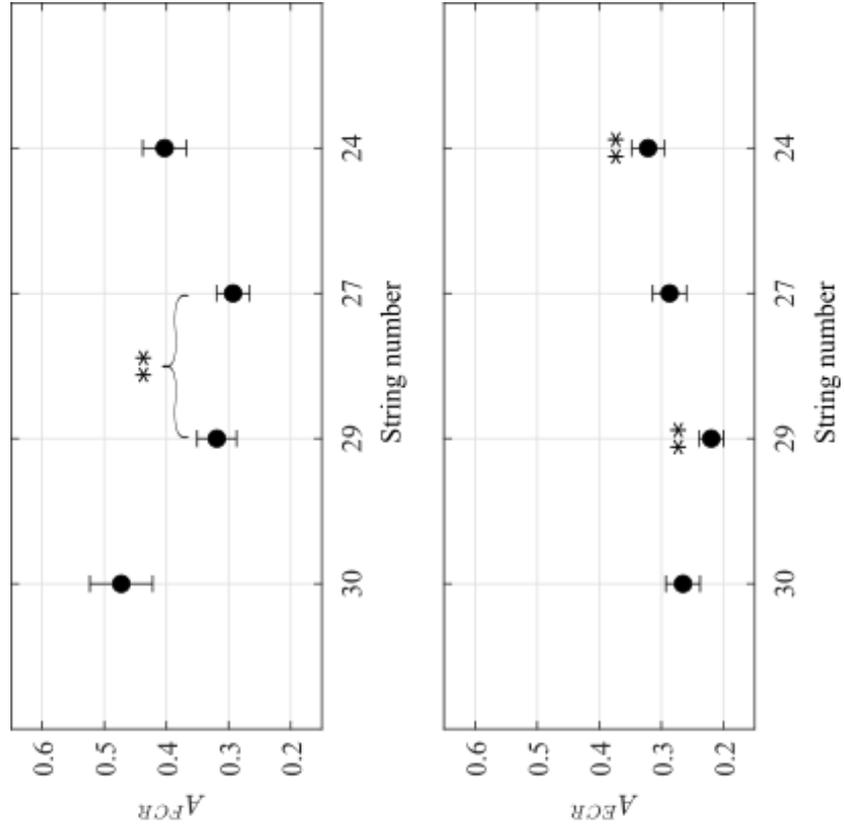


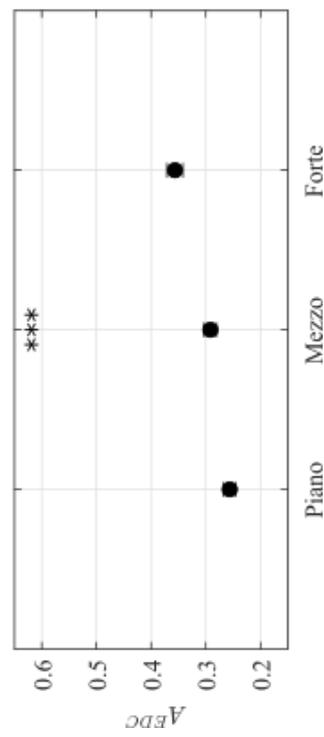
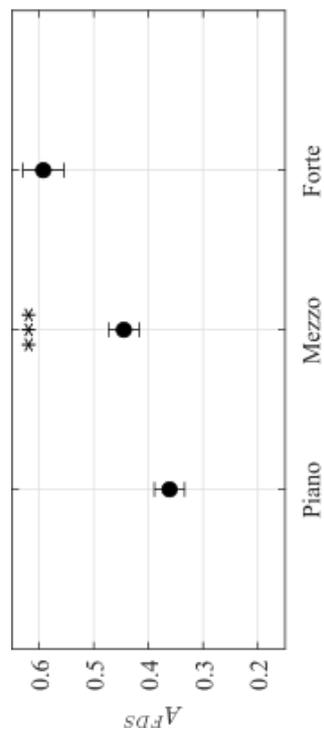
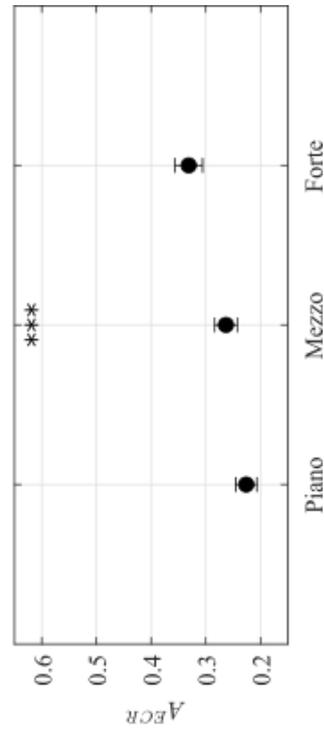
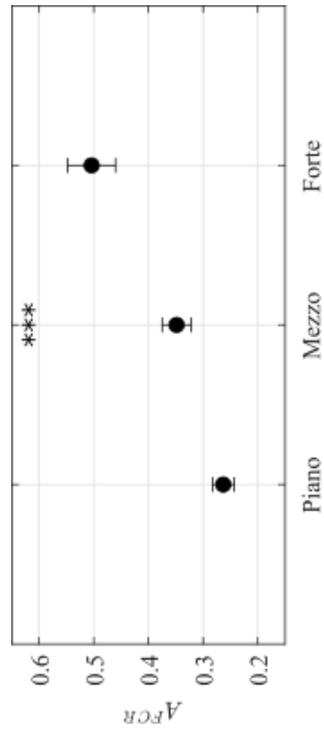


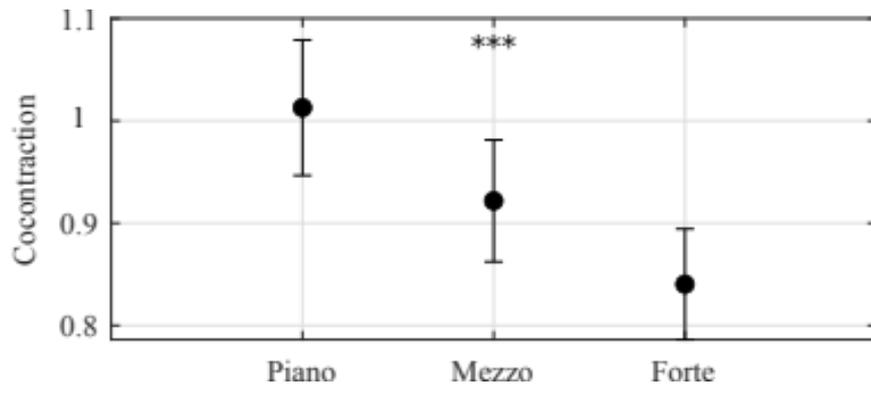




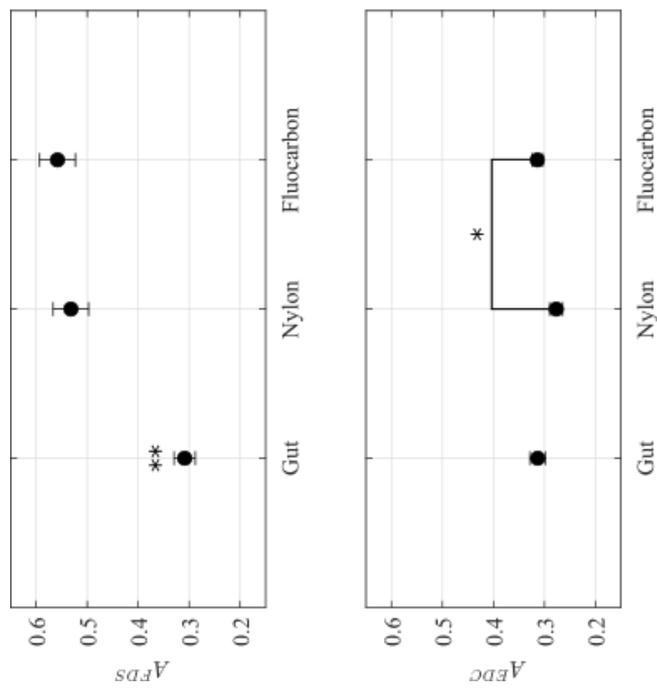
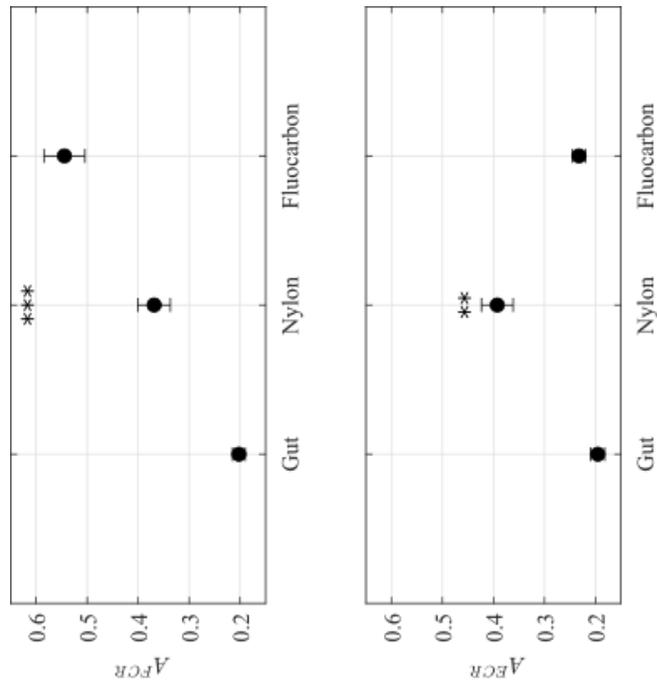


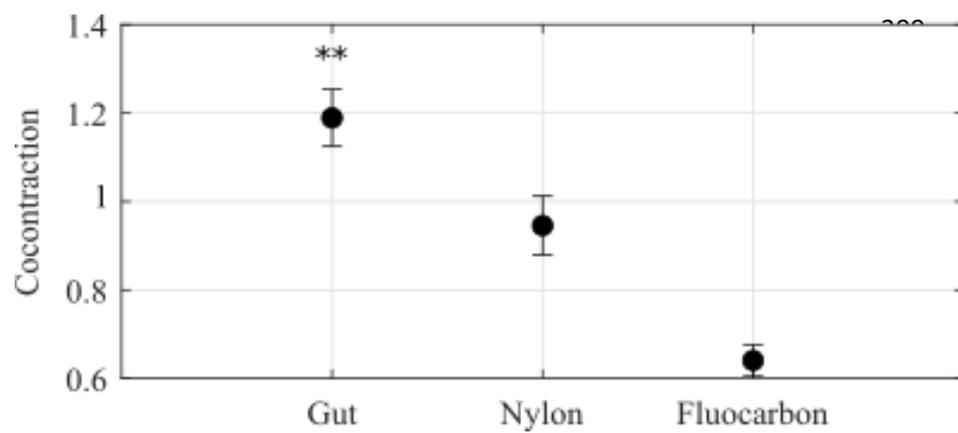






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400 **Figure Captions:**

401 Figure 1: Experimental setup.

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

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

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

411 Figure 5: RMS of the soundboard acceleration (L) for each investigated dynamics (*Piano*,
412 *Mezzoforte*, *Forte*) and stringing material (gut, nylon, fluocarbon) during arpeggio performance.
413 **, and *** indicate significant differences between the highlighted condition and all the other
414 conditions, and between all the conditions, respectively. The reported uncertainty represents a
415 95 % confidence interval.

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

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

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

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

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

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