Article

Intramuscular Oxygenation and Muscle Activity of Extensor Carpi Radialis Brevis During Piano Performance

An Observational Study

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BACKGROUND: Repetitive piano movements have been associated with playing-related musculoskeletal disorders (PRMDs) such as forearm myalgia and symptoms of lateral epicondylopathy. Despite the high prevalence of PRMDs among pianists, there is poor understanding regarding the underlying physiological mechanisms. Intramuscular oxygenation may play a role in the development of PRMDs. Therefore, this observational study aimed to explore the effect variability of playing piano repertoire on the oxygenation of the extensor carpi radialis brevis (ECRB). **METHODS:** Surface electromyography (EMG) activity and intramuscular oxygenation data (using near-infrared spectroscopy, NIRS) of the left and right ECRB were recorded in 13 conservatory piano students (8 female, 5 male, mean age 23.54 ± 3.24 years) while playing piano repertoire (virtuoso piece or études) for 20 minutes. From the oxygenation data, relative changes (in the percentage of the baseline measurements at rest) were calculated. **RESULTS:** For all participants, the oxygenated hemoglobin of the left ECRB over the piano play presented an averaged decline to the baseline resting value, with a sample mean for left ECRB of –7.48% and –11.88% for the right ECRB, ranging from –15.53% to –2.00% and –19.12% to –3.93%, respectively. The deoxygenated hemoglobin ranged in the left ECRB from –5.39% to 39.14% and from –9.37% to 54.01% in the right ECRB. The change in total hemoglobin ranged from –5.35% to 16.80% for the left ECRB and –12.10% to 10.37% for the right ECRB. EMG activity (in % maximal voluntary contraction) presented a mean of 16.85% (range 11.86 to 24.43) for the left ECRB and 23.65% (range 14.46 to 37.91) for the right ECRB. This pilot study presented a Pearson's *r* between the averaged oxygenated hemoglobin and EMG of –0.60 for the right ECRB and –0.48 for the left ECRB. **CONCLUSION:** Piano performance induced an average decline in oxygenated hemoglobin in the left and right ECRB, which differed largely between the specific pieces played. The EMG activity can partially explain these differences. Further research is needed to explore the impact of a 'dynamic index' reflecting the piece's dynamic characteristics and the individual oxygenation characteristics. *Med Probl Perform Art* 2023;38(4):214–223.

KEYWORDS: intramuscular oxygenation, extensor carpi radialis, conservatory piano students, performance-related musculoskeletal disorder, musician

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IN THE CONTEXT of professional piano playing, music students are predisposed to experiencing playing-related musculoskeletal disorders (PRMDs) affecting the upper limb and cervicothoracic junction (1). In a sample of 195 conservatory students piano, Bruno et al. (2008) presented point prevalences for elbow and forearm PRMDs of 5.5% and 24%, respectively (2). In a mixed sample of 200 professional pianists or piano students who presented hand and forearm pain solely attributed to overuse while playing the piano, Sakai et al. (2002) diagnosed 27 (13.5%) with lateral epicondylopathy (LE) (3). In a sample of 183 professional pianists, Monino et al. (2017) found point prevalences for LE of 6.2% in male and 4.2% in female pianists (4).

Repetitive loading of the tendon seems to initiate the pathological process of tendinopathy (5). Even under a low level of tendon loading, the repetitive work of office workers induces PRMDs (6,7). In a sample of 2210 office workers, Ranasinghe et al. (2011) presented 1-year prevalences of forearm and hands PRMDs of 15% for the right side, 4% for the left side, and 23% for bilateral (8). Piano performance involves a multitude of repeated key-striking with reaction forces at the fingertips around 2.3 N for weak sound dynamics up to 9.8 N for strong sound dynamics (9). This is comparably more than computer keystrokes presenting mean forces at the fingertip, from 0.80 N for the comma key to 1.25 N for the letter R (10). Pianists who train more than 20 hours weekly, play for more than 60 minutes without taking a break, and keep playing despite experiencing pain are at higher risk of developing musculoskeletal pain (11). These factors might thus also contribute to the development of tendinopathy. A state-of-the-art review on tendinopathy corroborates similar risk factors such as but not limited to overuse, lack of adequate recovery, highly repetitive movement, and poor ergonomics (12). Electromyography (EMG) studies have exposed altered muscle activation patterns and lower strength in the occurrence of LE and in patients with this condition (13). Moreover, the same review lists muscle weakness and deficits in neuromuscular control as intrinsic risk factors for the development of tendinopathy.

During physical exercise or intense piano playing, the contraction of the forearm muscles leads to compression, which subsequently induces alterations in the local microvascular perfusion of the muscles. These perfusion changes result in metabolic shifts and a consequent reduction in oxygen supply to the active muscle fibers (14). Even under low extensor carpi radialis (ECR) activation amplitude, long-term decreased intramuscular blood flow has been associated with the symptoms of LE (15,16). For the ECR, a significant reduction in muscle oxygenation during isometric contractions as low as 10% MVC has been demonstrated in patients with LE (17). Therefore, dysregulated oxygenation of the forearm muscles has been put forward as a potential contributor to the development of LE (18,19). However, it is unclear to what extent oxygenation reductions appear during the repetitive voluntary movements when playing the piano. Therefore, the goal of this study was to explore the effect variability of playing piano pieces on the oxygenation of the extensor carpi radialis brevis (ECRB).

METHODS

This study was approved by the Ethical Commission METC Z (Medische Ethische Commissie van Zuyderland en van Zuyd Hogeschool, record no. NL80159.096.21), officially recognized by the CCMO (Centrale Commissie Mensgebonden Onderzoek) which assesses the scientific and medical-ethical acceptability of research protocols. This study is explorative with monocentric data obtained by means of convenience sampling on conservatory piano students from the Conservatory of Maastricht. All subjects signed written informed consent.

Thirteen piano students (8 females, 5 males; mean age 23.54 ± 3.24 yrs) from the Conservatory of Maastricht (Hogeschool Zuyd) volunteered to participate in the study. They were informed about the study's purpose and procedures during a meeting prior to their participation The inclusion criteria for this study were being a male or female bachelor, master or postgraduate conservatory student piano. Exclusion criteria were: having a history of severe musculoskeletal injuries with medication or orthopaedic intervention; having a vascular disorder/pathology; self-reported severe musculoskeletal pain or discomfort (a score >7/10 on the numeric pain rating scale) (20).

Design

All measurements were done bilaterally, i.e., right and left ECRB. The protocol started with the pianists seated at rest, hands on the thighs. After 2 minutes, baseline measurements of the oxygenation of the ECRBs (time interval of 3 minutes) were taken. The baseline measurements were followed by surface EMG measurements of the MVC of 5 seconds, starting with the right ECRB and continuing with the left ECRB. After a minute, without warming up, the pianists continued with playing a piano repertoire for 20 minutes (virtuoso or *étude*) from their daily repetitions in the run-up to their exam performances. Both virtuoso pieces and *études* contained technical difficulties with velocity, complex technical structures, coordination, independence of left- and right-hand movements, and loudness of sound. The content of the pieces is presented in Table 1. EMG and oxygenation data of the left and right ECRB were captured during the piano performance.

NIRS

A calibrated near-infrared spectroscopy (NIRS) device (moorVMS-NIRS, moor instruments, Millwey, United Kingdom) non-invasively measured (in arbitrary units) the oxygenated (oxyHb), deoxygenated (deoxyHb), and total hemoglobin (totalHb) of the intramuscular area of the ECRB under the probe. Intramuscular oxygen saturation (SmO_2) represents the ratio (in %) of oxyHb/totalHb. Notably, myoglobin has the same absorbance spectrum as hemoglobin but absorbs at less than 10%, which is considered negligible (21,22). NIRS represents the dynamic balance between oxygen delivery and oxygen consumption (23) and is a valid and sensitive tool to monitor changes in muscle oxygenation and blood volume in human tissue (24).

The NIRS device contains a detector head consisting of two identical photodiodes and an emitter head with two near-infrared LEDs emitting light at approximately 750 and 850 nm. Those heads are directly placed on the corresponding skin area with a distance of 30 mm between them. To avoid interferences from sunlight, the probes were protected with adhesive tape (Hypafix, BSN medical GmbH, Hamburg, Germany). The sampling rate of the NIRS was 5 Hz. The precision is ±3% of the measured values (25).

TABLE 1. Characteristics of the Study Participants and Piano Excerpts

Age (yrs)	Gender	Instrument Experience (yrs)	Country of Origin	Scores
20	M	10	Belgium	Chopin Etude in C major op. 10/7 (from études)
23	F	13	Spain	Schumann Sonata 2 in G minor op.22 movement 1
19	F	12	Germany	Chopin Scherzo 1 in B minor op. 20
25	F	20	Portugal	Albright Sonata saxophone and piano—Poulenc Sextet op. 100 (movement 1)
18	F	12	Spain	Scriabin Etude
26	F	19	Spain	Liszt *Hungarian Rhapsody 6*
26	F	20	Turkey	Liszt *Mephisto Walz*
28	M	18	Germany	Ravel *Scarbo* (from *Gaspard de la Nuit*)
26	F	20	Columbia	Beethoven Sonata in D major op. 10/3 Presto
23	M	17	Romania	Schubert Sonata in C minor D958 movement 4 and Brahms Variations op.9 (selection) and Scarlatti Sonata
20	M	15	Belgium	Chopin Etude in G sharp minor op. 25/6 and Rachmaninov Paganini variations 14 &15 (*études*)
28	M	18	Germany	Liszt Sonata in B minor
24	F	17	Iceland	Hindemith *Ragtime* from Suite 1922

For each individual, the raw SmO_2, oxyHb, deoxyHb, and totalHb data during the piano performance were relatively expressed as percentage change from the preset baseline measurement's mean: oxyHb%, deoxyHb%, and totalHb%. For example,

$$\text{oxyHb\%} = \frac{\text{'oxyHb during the performance'} - \text{'oxyHb at baseline'}}{\text{'oxyHb at baseline'}} * 100$$

For each individual, the averages on the oxyHb%, deoxyHb%, and totalHb% arrays were calculated over the total time interval of the piano play. The data array of this output variable was labelled with the prefix '**d_**': d_SmO_2, d_oxyHb, d_deoxyHb, and d_totalHb.

EMG

EMG activity was retrieved with a semi-wireless EMG device (Biosignalplux, Lisbon, Portugal) at a sampling rate of 1,000 Hz (gain 1,000; range ±1.5mV; bandwidth 25–500 Hz; input impedance >100 GΩ; common mode rejection ratio 100 dB). For each site, two self-adhesive, disposable, pregelled surface Ag–AgCl electrodes were attached to the skin in line with the muscle fibers (Biosignalplux, Lisbon, Portugal). The recommendations of Barbero, Merletti, and Rainoldi (2012) (26) were followed for the correct placement of the electrodes. The interelectrode center-to-center distance was 20 mm. Before electrode attachment, the skin was dry scrubbed and rubbed with an ether/alcohol mixture. On the ECRB muscle, electrodes were placed perpendicularly under the external rim of the NIRS probe shield. A ground electrode was applied at the processus styloideus of the right radius. The EMG signal amplitude was analyzed following a 2nd-order Savitzky Golay digital filter (frame length 15).

MVC activity was measured over 5 seconds. The median from the middle 3 seconds was calculated. This median MVC was used as reference value to standardize the amplitude of the EMG data (in %MVC), labelled as EMG. The algorithms were programmed in Matlab (Matlab ver. 2020b; MatLab, Natick, MA, USA).

Statistical Analysis

IBM SPSS Statistics 28 and JASP 0.17 were used for the statistical analysis. This study is an exploratory study based on convenience sampling and as such underpowered to achieve statistical significance at the commonly used 5% level. For instance, a priori power analysis presented a sample size of 64 participants for a correlation with moderate effect size, power of 0.8 and alpha 0.05. Normal distribution was checked using formal Shapiro-Wilk testing (SW), Q-Q plotting, and visual inspection of the histograms with normality plots. Mean, median, standard deviation (SD), 1st (Q1) and 3rd quartile (Q3), inter quartile range (IQR), and minimum and maximum values were calculated. 95% confidence intervals (95% CI) for the mean and median were calculated using bootstrapping (1,000 samples). Descriptive statistics also incorporated the robust mean absolute deviation (MAD_R) (27). Furthermore, the Bayesian framework was added for inferential statistics as an alternative approach to the frequentist approach. It allows prior beliefs about the intervention combined with the observed data to form posterior responses about the outcome of interest. The Bayes factor (B_{10}) presents the ratio of the likelihood of the alternative hypothesis (H_1) to the likelihood of the zero hypothesis (H_0) (28). Bayesian procedures were used for the inferential statistics on correlations.

RESULTS

Since this study is an exploratory pilot, the data are presented and discussed with a main focus on the variability and individual characteristics of the output. In this context, the raincloud plot is a very useful tool.

To provide a view of the variability in the oxygenation and electromyographic individual dynamic profiles during the piano performance, the data arrays of the output variables d_oxyHb% and EMG (in %MVC) of the right ECRB were smoothed using a moving average with a time

TABLE 2. Descriptive Statistics of the Oxygenation Output Variables and Electromyographic Activity of the ECR During Piano Performance

Parametric Descriptives	Mean	CI95% Upper	CI95% Lower	s	S-W	S-W (p)	Minimum	Maximum
Left								
d_SmO_2	–12.09	–8.58	–15.60	6.46	0.80	0.01	–18.04	–0.84
d_oxyHb	–7.42	–5.21	–9.76	4.17	0.95	0.58	–15.53	–2.00
d_deoxyHb	15.17	23.35	7.00	15.04	0.94	0.46	–5.39	39.14
d_totalHb	4.66	7.96	1.35	6.08	0.99	1.00	–5.35	16.80
EMG (%MVC)	16.85	18.76	14.94	3.51	0.95	0.52	11.86	24.43
Right								
d_SmO_2	–12.23	–8.41	–16.04	7.02	0.89	0.10	–21.05	–1.92
d_oxyHb	–11.88	–9.21	–14.55	4.91	0.95	0.60	–19.12	–3.93
d_deoxyHb	18.67	30.22	7.12	21.25	0.94	0.43	–9.37	54.01
d_totalHb	–0.80	3.13	–4.74	7.24	0.96	0.78	–12.10	10.38
EMG (%MVC)	23.65	27.17	20.13	6.47	0.95	0.55	14.46	37.91

Non-Parametric Descriptives	Median	CI95% Upper	CI95% Lower	Q1	Q3	IQR	MAD	MAD_R
Left								
d_SmO_2	–15.67	–8.97	–16.65	–16.65	–8.97	7.68	2.22	3.29
d_oxyHb	–6.39	–4.27	–10.04	–9.81	–3.92	5.89	2.67	3.96
d_deoxyHb	13.82	25.73	6.67	6.67	25.73	19.06	11.91	17.66
d_totalHb	4.72	7.98	–0.59	0.75	7.98	7.23	3.97	5.89
EMG (%MVC)	16.36	18.70	15.63	15.63	18.70	3.07	2.34	3.47
Right								
d_SmO_2	–14.22	–15.25	–19.05	–19.05	–6.59	12.46	5.51	8.17
d_oxyHb	–11.04	–8.82	–15.25	–15.25	–8.82	6.43	3.66	5.42
d_deoxyHb	12.07	31.24	4.19	4.19	31.25	27.05	18.23	27.03
d_totalHb	–1.10	5.03	–4.90	–4.90	5.03	9.93	6.13	9.09
EMG (%MVC)	22.62	26.54	19.14	19.14	26.54	7.39	3.78	5.60

MAD = mean absolute deviation, MAD_R = MAD robust, IQR = interquartile range, S-W = Shapiro-Wilk score, S-W (p) = S-W *p*-value, Q = quartile. The prefix 'd_' refers to the averaged % change of the oxygenation variables during the piano play (SmO_2 =intramuscular oxygen saturation; oxyHb = oxygenated hemoglobin, deoxyHb = deoxygenated hemoglobin, totalHb = total hemoglobin. EMG% = averaged electromyographic activity during the piano performance in % MVC).

window of 20 seconds. The time interval presented in the graphs (Appendix Fig. 2) was between 3 and 18 minutes of the piano performance.

Descriptive Statistics

The sample encompassed 8 female and 5 male conservatory students piano, with a mean age of 23.8 (3.6) and 23.4 (3.0) years, respectively.

'd_' Oxygenation Output Variables

The descriptive statistics of the **'d_'** oxygenation output variables and EMG activity of the left and right ECRB are presented in Table 2, separately for the left and right ECRB.

A high range of EMG activity was observed between the cases, from a minimum of 11.86 to 24.43 (%MVC) for the left ECRB and 14.46 to 37.91 (%MVC) for the right ECRB (Fig.2). d_SmO_2 presented minimum and maximum values of respectively –18.04 to –0.84% for left and –21.05 to –1.92% for right; d_deoxyHb, –5.39 to 39.14% for left and –9.37 to 54.01% for right; and d_totalHb, from –5.35 to 16.80% for left and –12.10 to 10.38% for right.

As represented in the raincloud difference plots (Fig. 1), 7 of the 13 excerpt cases presented with a higher d_oxyHb for the right ECRB, the difference ranging from 6.30 to 13.61%. In 4 of the 13 excerpts, a difference of <1% was observed. In one case, the left ECRB presented with a higher d_oxyHb (difference 4.95%) (Appendix Fig. 1).

EMG Activity

A high range of EMG activity was observed between the cases, from a minimum of 11.86 to 24.43 (%MVC) for the left ECRB and 14.46 to 37.91 (%MVC) for the right ECRB. 12 of the 15 cases within the sample presented a higher EMG activity for the right ECRB (3 of them with a difference < 3%) (Fig. 2). One excerpt presented with the left ECRB EMG activity being higher than the right, but the difference was small (1.73%). No significant correlation was present between left and right EMG (Pearson r = 0.194, p = 0.526, BF_{10} = 0.41).

Figure 3 presents the scatterplots between d_oxyHb and EMG for the left and right ECRB. A significant negative Pearson's r correlation of –0.480 (p = 0.05) was observed in the sample between d_oxyHb and EMG of the left ECRB. A significant negative Pearson's r correlation of –0.595 (p = 0.016) was observed between d_oxyHb and EMG of the right ECRB. With a Bayesian approach, a prior uniform distribution was specified with a negative relationship and, following the Bayes factor robustness check, a stretched beta prior κ of 0.3238 for the left ECRB and 0.5633 for the right ECRB. The posterior distribution on the correlation between EMG and d_oxyHb was characterized for the left

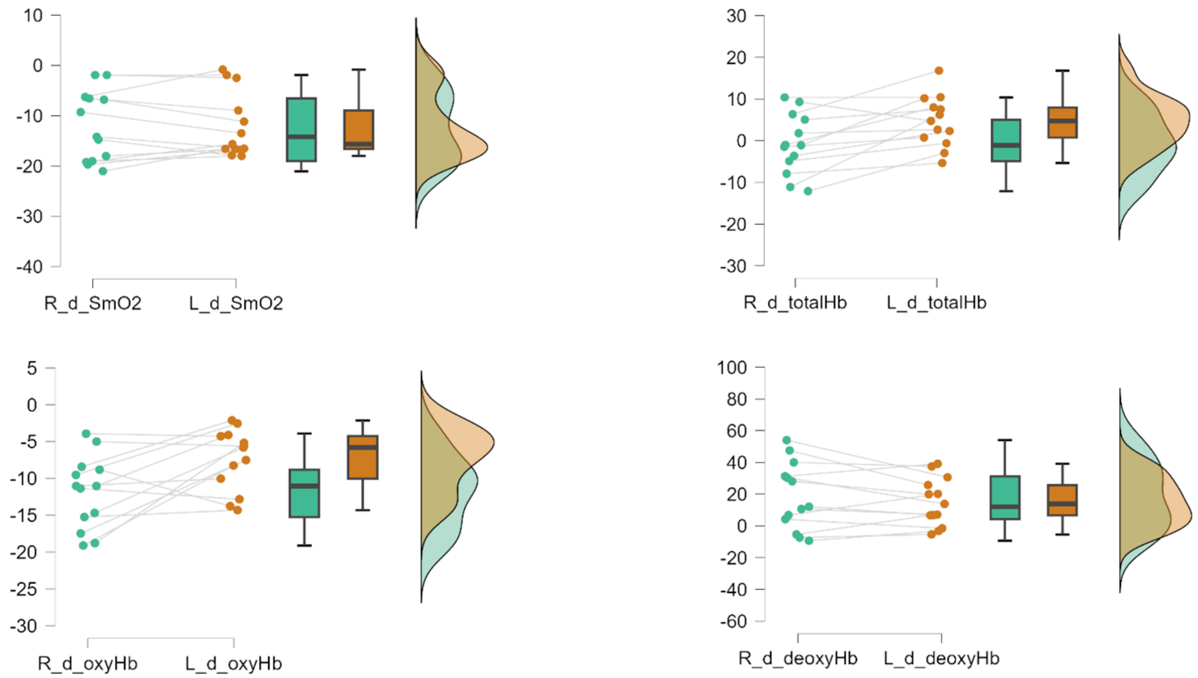

FIGURE 1. Raincloud plots of the 'd_' oxygenation variables.

side with a median = –0.418 (credible interval [–0.778, –0.047], BF_{10} = 2.724) and for the right side with a median = –0.508 (credible interval 95% [–0.832, –0.034], BF_{10} = 2.735). The Bayes factor BF_{10} compares the predictive likelihood of H_1 to H_2 [BF_{10} = p(data\$H_1$)/p(data\$H_0$)].

As presented in Appendix Fig. 2, the patterns of EMG activity and oxyHb differ in fluctuations between the different piano pieces.

DISCUSSION

The present study explored the piano performance of selected repertoire on the oxygenation of the left and right ECRB using NIRS and EMG.

Left Extensor Carpi Radialis Muscle

On average, all participants' oxyHb levels during the piano play were consistently lower than the baseline resting value. The sample mean for d_oxyHb was –7.48% (range –15.53% to –2.00%), suggesting a decline in oxygenated hemoglobin supply to the muscle during the task. The SmO_2Hb variable, which represents the saturation level of oxygenated hemoglobin, showed a mean decrease for d_SmO_2 of –12.90% (range –18.04% to –0.84%), indicating the notion of declined oxygen supply to the left ECRB muscle while playing the piano. These findings are consistent with the study by Heiden et al. (2005), which also demonstrated a decrease in oxygen saturation in the ECRB muscle during a demanding computer mouse task (15). The authors also reported higher ratings of tenseness and fatigue in participants performing the task (15). Translating these findings to piano players could suggest a potential role of oxygenation decline in developing forearm-related PRMDs.

Furthermore, the variables d_deoxyHb and d_totalHB, which represent the changes in deoxygenated hemoglobin and total hemoglobin, respectively, also exhibited large ranges of values among participants. The mean change in deoxyHb was 14.98% (range –5.39% to 39.14%). The mean

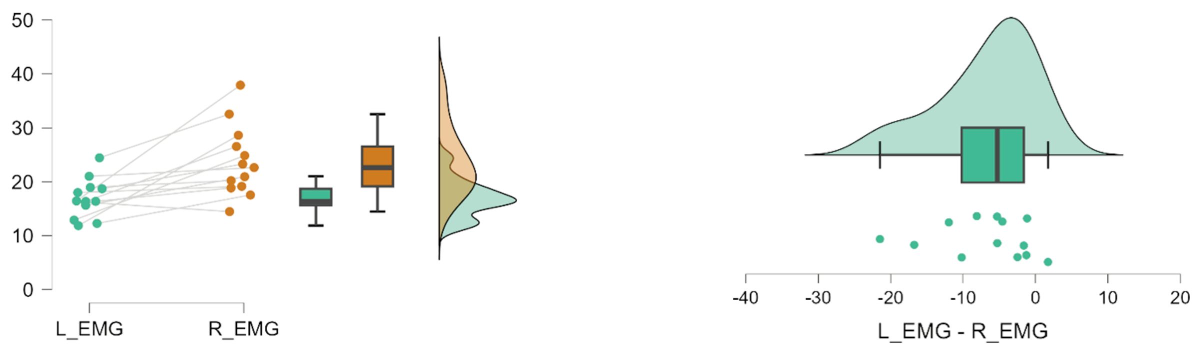

FIGURE 2. Raincloud plots of EMG activity of the left and right ECRB.

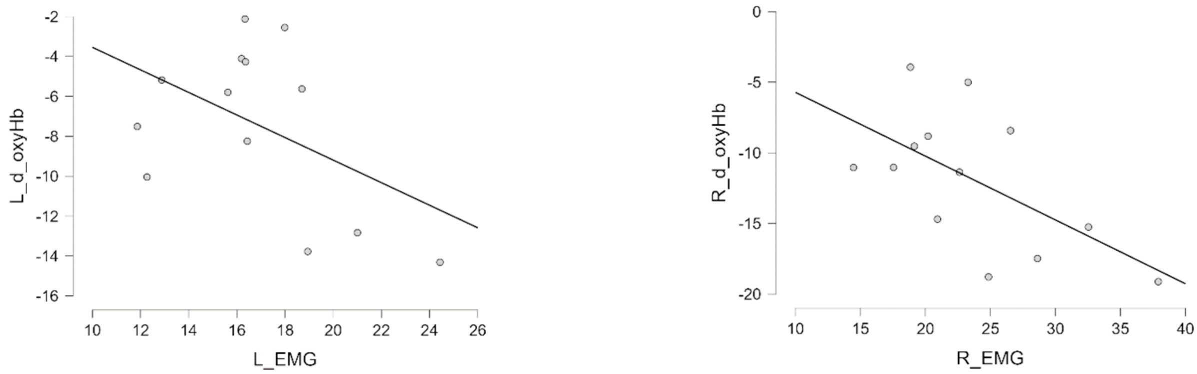

FIGURE 3. Scatterplot between d_oxyHb and EMG for left and right ECRB.

change in totalHb was 4.66% (range –5.35% to 16.80%), which aligns with Crenshaw and colleagues' (2006) findings during computer mouse work (29). These findings suggest significant variability in the metabolic demands and blood flow patterns within the left ECRB during piano performance. EMG data revealed an average muscle activation level of 16.85% of MVC (range 11.86% to 24.43% MVC) during piano performance. This provides insights into the level of muscular effort exerted by piano players during piano performance and can help assess the degree of muscle recruitment and activity in response to the demands of a piano score.

Overall, the NIRS and EMG data collectively suggest that the left ECRB muscle experienced a decline in oxygen supply and exhibited variations in metabolic demands and muscle activation levels during piano performance. These findings could contribute to our understanding of the physiological mechanisms of PRMDs in pianists, as previous work demonstrated that forearm work-related myalgia was associated with an increased reliance on nonoxidative metabolism (30). One of the main contributors to this phenomenon is a reduction in local muscle blood flow and perfusion (30).

Right Extensor Carpi Radialis Muscle

The results obtained from the right ECRB muscle mirror similar findings to the left ECRB muscle, demonstrating for all participants a consistently reduced average oxyHB level during piano performance.

The d_oxyHb variable in the right ECRB exhibited a sample mean decrease of –11.88%, ranging from a minimum of –19.12% to a maximum of –3.93%. This indicates that there was a consistent reduction in oxyHb levels in the muscle compared to the baseline resting state. Also, d_SmO_2HB showed a mean decrease of –12.23% (range –21.05% to –1.92%). These findings suggest a decline in the oxygen supply to the right ECRB muscle during the piano-playing task. The d_deoxyHb (changes in deoxygenated hemoglobin) and d_totalHb (changes in total hemoglobin) variables also exhibited large-ranging values, indicating significant variations in the metabolic demands and blood flow patterns within the right ECRB muscle. The mean change in deoxygenated hemoglobin was 18.67%, ranging from –9.37% to 54.01%. The mean change in total hemoglobin was –0.80%, ranging from –12.10% to 10.37%. These variations suggest diverse metabolic responses and blood flow regulation within the muscle, potentially influenced by the dynamic characteristics and intensity of the piano repertoire performed during the study. Additionally, the right EMG activity showed a sample mean of 23.65% of MVC, ranging from a minimum of 14.46% to a maximum of 37.91%. The variability in EMG activity may reflect differences in the intensity of muscle engagement and the dynamic characteristics of the non-standardized piano plays. These differences can arise from variations in velocity, loudness, and complexity of the piano repertoire performed over time.

In summary, the results from the right ECRB muscle demonstrate a consistent decline in oxygenation variables, indicative of impaired oxygen supply during piano playing. The large variability observed in these variables can be attributed to the non-standardized nature of piano playing, encompassing variations in muscle activity intensity and the dynamic characteristics of the piano repertoire. These findings shed light on the individual and task-related factors that influence the physiological responses of the right ECRB muscle during piano performance.

Correlation Analysis NIRS and EMG Data During Piano Performance

This exploratory study found a Pearson's sample correlation coefficient (r) of –0.60 for the right ECRB and –0.48 for the left ECRB, representing the relationship between the d_oxyHb (changes in oxygenated hemoglobin) and EMG activity. The determination coefficient (r^2) indicates the proportion of variability in the deficit of intramuscular oxyHb that can be attributed to the level of muscle activation. In this study, the r^2 value for the right side was 0.36, suggesting that 36% of the variability in the deficit of intramuscular oxyHb during piano performances could be explained by the level of muscle activation. Similarly, the r^2 value for the left side was 0.23. These values indicate a moderate relationship between the two variables. The obtained correlations align in magnitude with previous findings by Elcadi, Forsman, and Crenshaw (2011) who investigated submaximal isometric contractions of the ECR muscle. They found that submaximal isometric contractions at target levels of 10, 30, 50 and 70% MVC of the ECR induced changes in intramuscular oxygenation (31). Their study reported a correlation coefficient of –0.54 ($p < 0.001$) between the percent change in intramuscular oxygenation and surface EMG activity (expressed in %MVC) during different target levels of muscle contraction.

Intra-individually, higher muscle activation has been observed when playing the piano louder or faster (32-34). The findings in this study suggest that inter-individually, while there is a significant but moderate correlation between the deficit in intramuscular oxygenation and muscle activation during piano performances, other factors may also contribute to the variability in the oxygenation variables observed. The variability in the dynamic context of piano playing (as demonstrated in the individual time profiles of oxyHb and EMG in Appendix Fig. 2), the complexity of muscle coordination and motor control required for performing intricate piano pieces as well as the individual physiological characteristics of oxygenation may influence the relationship between oxygenation deficit and muscle activation.

Limitations and Future Research

This explorative study encompassed an underpowered sample of only 13 rather heterogenous piano students. Consequently, the results should be interpreted cautiously as 'first hints' rather than following the Bayesian language with moderate or anecdotal evidence.

The limited relationship observed between oxyHb decline and EMG activity of the ECRB during piano performance can be attributed to various factors. The main factors include inter-individual characteristics, the validity of MVC procedure and the dynamic characteristics of the piano repertoire. Inter-individual characteristics may lead to variations in oxygenation supply and metabolism in response to dynamic muscle activation and thus may contribute to the diverse relationship observed among individuals. Future research should therefore explore the inter-individual factors influencing oxygenation responses during piano playing. The validity of the MVC procedure remains a topic of discussion, with many unknowns yet to be resolved (35). In this study, the MVC procedure involved forceful wrist extension against manual resistance with the elbow in 90° flexion and the supported forearm in pronation. Future research should consider implementing alternative MVC procedures, such as the "pull test" described by Aki et al. (2020), demonstrating clear MVC activation in the ECRB muscle. Exploring different MVC protocols may provide further insights into the relationship between oxyHb deficit and muscle activation. The specific dynamic characteristics of the piano repertoire performed can influence the relationship between oxyHb deficit and muscle activation. Piano music often exhibits distinct time patterns with alternating higher and lower muscle activation periods, potentially affecting the recovery of oxyHb levels (36,37). Future research should consider developing a "dynamic index" that incorporates amplitude levels linked to the time patterning of muscle activity during piano performance. The combination of a certain level on the dynamic index of specific repertoire with the individual oxygenation characteristics emphasizes the need of an interactive person-centered approach to pianists in the prevention and treatment of PRMDs. From a physiological point of view, the clinical question in this context is whether the individual pianist meets the physical requirements to cope with his/her choice of repertoire? Besides biomechanics (coordination, proximal/distal sequencing, etc.), work schedule and psychology (performance anxiety, etc.), future research should explore whether the dynamic profile of the piano play as well as the individual's characteristics of oxygenation might play a key role to answer this question.

Conclusion

Piano performance decreases the intramuscular oxyHb in the left and right ECRB, which differs with the specific piece being played. The EMG activity can partially explain this. Further research is needed to explore the impact of a 'dynamic index' reflecting the dynamic characteristics of the repertoire played. Together, attention should be given to the individual physiological characteristics of the oxygen supply.

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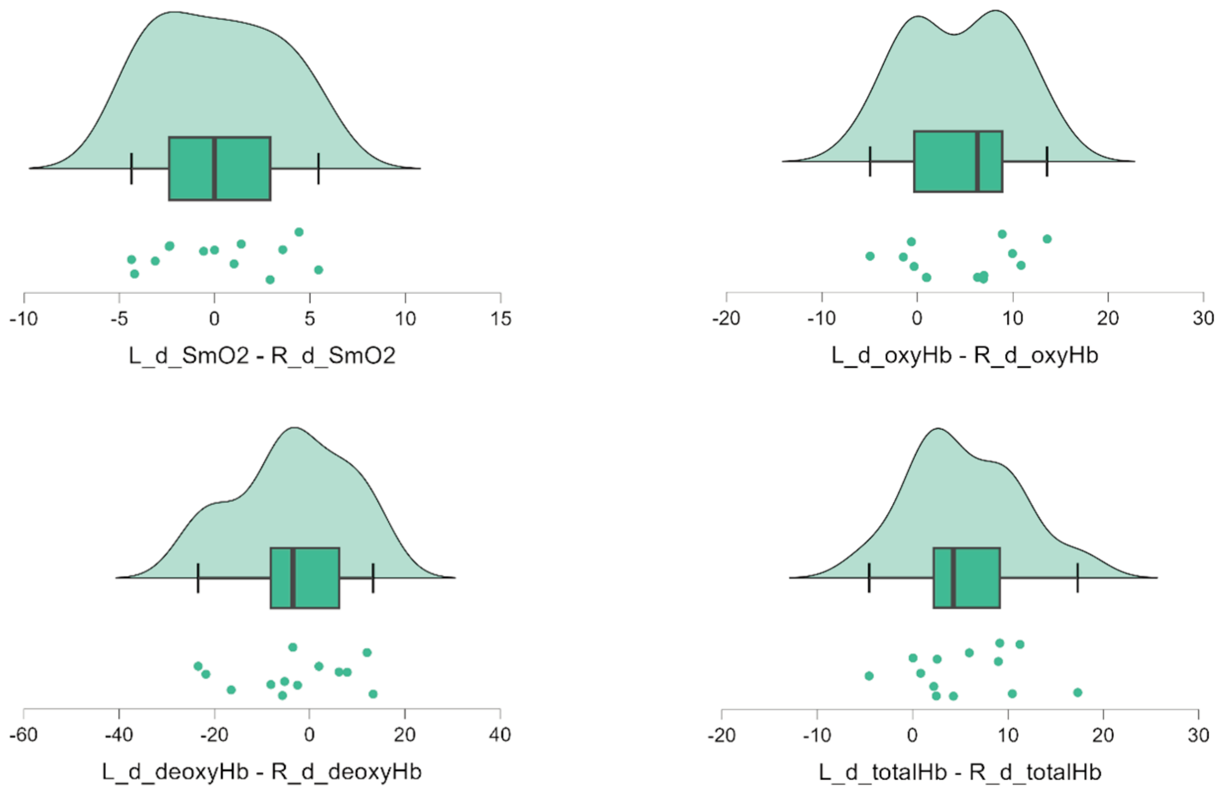
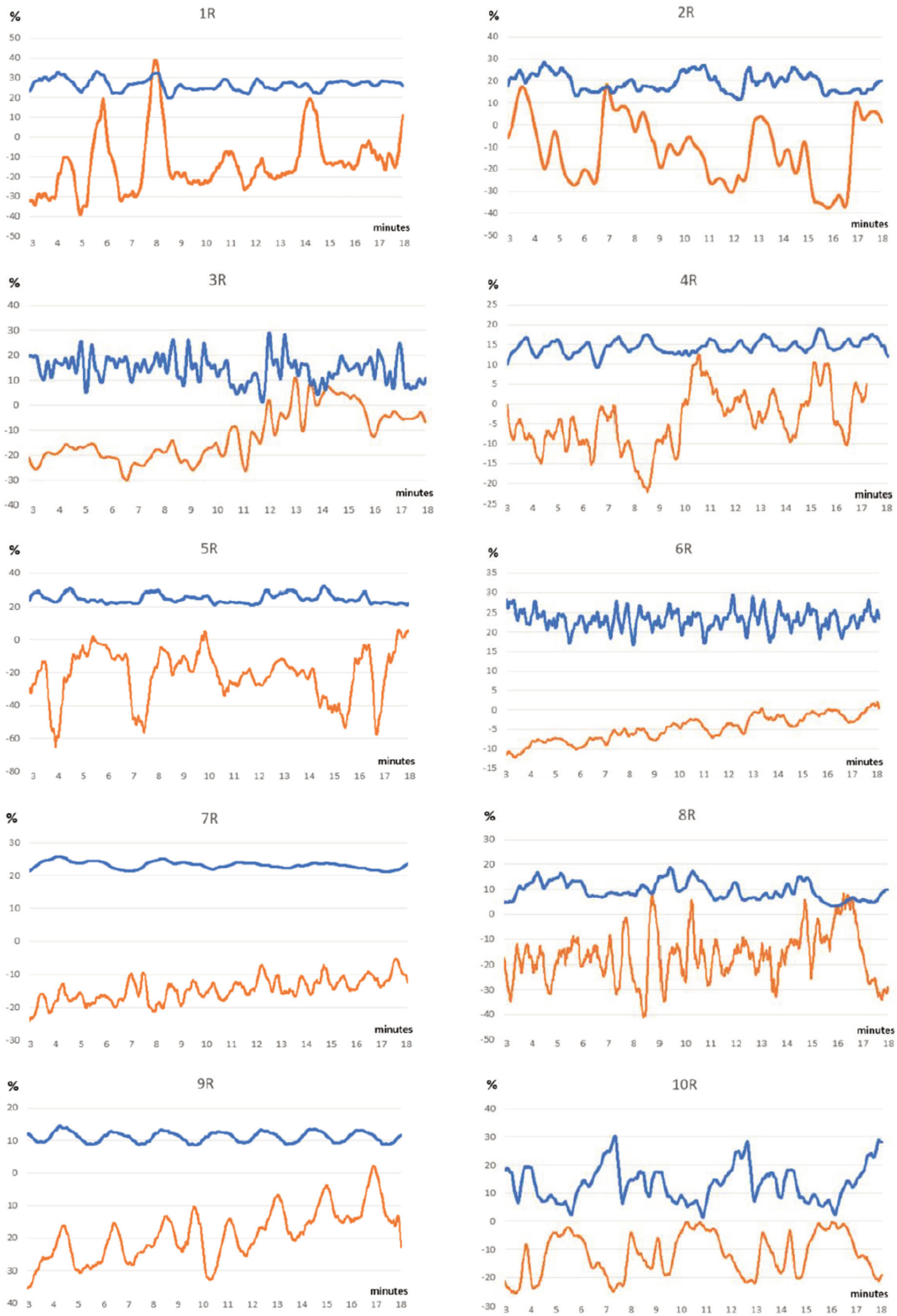


APPENDIX FIGURE 1. Raincloud difference plots between left and right side of the 'd_' oxygenation variables.



APPENDIX FIGURE 2. Individual time profiles of EMG activity and d_oxyHb during piano play. The *blue line* indicates EMG (in %MVC), and *orange line* = d_oxyHb (in %). Graph reference: number = participants' reference; Abscis = time (in minutes), ordinate = %; Time interval = between 3 and 18 minutes of the 20-minute piano play.