Technische Universität München

# The Influence of Different Playing Speeds on Muscle Activity in the Back, Upper Arm, and Forearm in Skilled Piano Playing

## Einfluss von unterschiedlichen Spielgeschwindigkeiten auf die Muskelaktivität in Rücken, Ober- und Unterarm bei erfahrenen Pianist*innen

Master thesis for the attainment of the degree

**M.Sc. Sport and Exercise Science**

at the Department of Sport and Health Sciences, Technical University of Munich

**Supervisor** Clara Günter, M.Sc.

Associate Professorship of Neuromuscular Diagnostics

**Examiner** Prof. Dr. David Franklin

Associate Professorship of Neuromuscular Diagnostics

**Submitted by** Ho Huang

6020 Innsbruck, Austria

**Submitted on** Munich, the 4th of December 2022

# Erklärung / Declaration

Ich erkläre hiermit ehrenwörtlich, dass ich die vorliegende Arbeit selbständig angefertigt habe. Die aus fremden Quellen direkt und indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde weder einer anderen Prüfungsbehörde vorgelegt noch veröffentlicht.

I hereby declare that the thesis submitted is my own unaided work. All direct or indirect sources used are acknowledged as references. This paper has not previously been presented to another examination board or published.

Innsbruck, 04.12.2022

Ort, Datum, Unterschrift / Place, date, signature

**Abstract**

Pianists are able to demonstrate extraordinarily fine movement control and simultaneously take other elements of music into consideration, even at considerable playing speeds. Previous studies have revealed different upper extremity movement organisation between expert pianists and novice piano players. Nevertheless, the change of skilled pianists' muscle activity in response to different playing speeds was unclear. This study's aim is to investigate the influence of different playing speeds on muscle activity in skilled pianists' back, upper arm, and forearm. In the study, four female pianists played a classical music piece at slow, medium, and fast tempi (60, 90, and 120 bpm, respectively). Electromyography (EMG) and the Musical Instrument Digital Interface (MIDI) data was gathered throughout the entire performance and analysed. Our results identified the least amount of muscle activity at the slow tempo, whereas the highest amount of activity at the fast tempo. From tempo 90 to 120 bpm, muscle activity from the back and most of the forearm muscles demonstrated a statistically significant upswing. Counterintuitively, regardless of the increase in muscle activity between tempo 60 and 90 bpm from most of the muscles, none of them were statistically significant different. Our findings suppose that pianists may be capable of performing at a range of different playing speeds without increasing their muscle activities. However, beyond this range of playing speeds, a different motor behaviour may be required in order to respond to a higher demand from the neuromuscular system. This study lays the groundwork for research regarding muscle activity in piano playing at a higher level of proficiency. Future studies could investigate muscle synergies and co-contractions in response to different playing speeds to further explore the mechanisms of pianists' ability to play at fast tempi.

*Keywords:* muscle activities, MIDI, electromyography (EMG), piano playing, tempo, key pressing velocity

## Contents

Introduction ........ 6
Method ........ 9
  Participants ........ 9
  Experimental Design and Procedures ........ 11
  Data Acquisition ........ 13
  Data Analysis ........ 13
  Statistical analysis ........ 14
Results ........ 15
  EMG Data ........ 15
  Key Pressing Velocity Data ........ 21
Discussion ........ 25
References ........ 32
Appendix A. Edinburgh Handedness Inventory ........ 34
Appendix B. Prelude in C Minor, BWV 847 ........ 35
Appendix C. Music Education Background Questionnaire ........ 37
Appendix D. B Major Scale and Four Variations ........ 39
Appendix E. Transcription of the MIDI Note Numbers ........ 40
Appendix F. Bar-to-Bar Muscle Activity in Each Muscle ........ 41
Appendix G. Bar-to-Bar Mean Normalised RMS Scores in Each Muscle ........ 45
Appendix H. Key Pressing Velocities from the Left and the Right Hand ........ 53

# List of Figures and Tables

## Figures

Figure 1 Excerpt from the Prelude in C Minor, BWV 847 .......... 10
Figure 2 Experimental Design of the Study .......... 11
Figure 3 Muscle Activity in Each Muscle .......... 16
Figure 4 Bar-to-Bar Muscle Activity in Latissimus Dorsi .......... 19
Figure 5 Bar-to-Bar Muscle Activity in Biceps Brachii .......... 20
Figure 6 Bar-to-Bar Muscle Activity in Flexor Digitorum Superficialis .......... 20
Figure 7 Key Pressing Velocity from the Left and the Right Hand .......... 22
Figure 8 Bar-to-Bar Key-Pressing Velocities from the Left Hand .......... 23
Figure 9 Bar-to-Bar Key-Pressing Velocities from the Right Hand .......... 24

## Tables

Table 1 Means and Standard Deviations of the Normalised RMS Scores .......... 17
Table 2 Results of the One-Way Repeated Measures ANOVA Test .......... 18
Table 3 Results of the Bonferroni Post Hoc Test .......... 18

## Introduction

Pianists are capable of demonstrating extraordinarily fine movement control and simultaneously taking other elements of music such as rhythm, texture, and dynamics into consideration, even at considerable playing speeds (Ericsson & Lehmann, 1996). This prompts questions such as: how do pianists acquire the ability to execute complicated movements so accurately and elegantly, how does the brain programme and execute movement plans, and how does the neuromuscular system react and respond? In order to discover the answers, researchers have adopted different approaches and gathered evidence from various fields (Bove et al., 2007; Hirano, Kimoto, & Furuya, 2020; van Vugt, Furuya, Vauth, Jabusch, & Altenmüller, 2014).

Research findings in kinematic analysis and muscle activity regarding piano playing revealed that expert pianists and novice piano players organised their upper extremity movements differently (S. Furuya & Kinoshita, 2007). While performing an octave key pressing task with the thumb and little finger at a slow tempo, expert pianists demonstrated a clear proximal-to-distal sequencing from the shoulder through the elbow to the wrist joints, whilst novice piano players did not. The authors further confirmed that the difference in movement strategies between experts and novices started already before the moment of finger-key contact. (S. Furuya, Goda, Katayose, Miwa, & Nagata, 2011; S. Furuya & Kinoshita, 2007; Shinichi Furuya & Kinoshita, 2008). Regardless of the playing volume, experts started the key pressing task with a shoulder flexion, leading to a greater key pressing angle (the internal angle between a finger and a key) at the finger-key contact moment. From the finger-key contact moment till the key was fully pressed, they flexed the shoulder, wrist, and metacarpophalangeal joint, extended the elbow, and used their fingertips as a pivot point to increase the key pressing angle. Conversely, the novices extended the shoulder joint before and after the finger-key contact moment and used primarily wrist flexion and elbow extension to complete the task. Additionally, the electromyography (EMG) data displayed a loudness-dependent co-contraction of the upper limb muscles for both experts and novices from the short period of time prior to the finger-key contact moment till just before key release. However, the index value of co-contraction in the forearm of the experts was observed to be less than that of the novices.

Having known the different movement strategies adopted between expert pianists and novice piano players, we conducted a case-study with a recreational piano player in an attempt to induce the aforesaid proximal-to-distal sequencing observed in experts to improve the loudness and contrast of dynamics in piano playing (Huang, Forano, & Franklin, 2021). In this study, an excerpt of a classical music piece as well as a downward ball-throwing exercise were used. The results not only showed the improvement in the dynamic range of the performance and the changes in muscle activity after the intervention, but also indicated the use of the back muscles while piano playing.

Nevertheless, it was unclear whether the movement organisation and the coordination across joints while piano playing varied at different playing speeds. Furuya et al. compared the hand and arm movements between professional and recreational pianists who had no previous professional music education (S. Furuya, Goda, et al., 2011). They observed that professional pianists demonstrated smaller increase in finger muscle co-contraction but greater elbow velocity as the playing speed increased when playing two keys with the thumb and little finger alternately at various tempi. Furthermore, when playing the keys as fast as possible, difference in playing speeds among participants were associated with their elbow velocities but not the digit velocities, indicating that proximal joint motion may contribute more when playing fast. Other studies, focused on hand kinematics, showed that the coordination pattern of fingers, specifically metacarpophalangeal and proximal-interphalangeal joints from the index, middle, ring, and little fingers were similar across different playing tempi among professional pianists (S. Furuya, Flanders, & Soechting, 2011; S. Furuya & Soechting, 2012). The results were also in line with a later study which quantified pianists' hand and finger joints' contribution to a key reaching movement (Goebl & Palmer, 2013). They found that the contributions of each individual joint remained similar across different tempi and only the wrist movement contributed slightly more to the fingertip motion at faster tempi.

Later on, another finding was published in regard to muscle activities from the finger flexors and extensors in piano playing (Chong, Kim, & Yoo, 2015). Ten male adults who received less than three years keyboard playing training, and no professional music education within the past 10 years, were asked to play five keys (C, D, E, F, and G) with different patterns at their most comfortable tempo and at their fastest tempo. The findings indicated that the fast-playing tempo elicited higher electromyography (EMG) amplitudes in comparison to the slow tempo. Additionally, not only was greater muscle activity observed while pressing the keys successively than individually, but also the movement sequences with non-adjacent fingers were proved to require higher motor commands. Nonetheless, the margin of the differences between the fast and slow playing speeds varied among participants in this study. Furthermore, whether these findings apply to skilled pianists, longer pieces of music, or can be observed in other upper body muscles has yet to be proven.

Based on the literature and following the field’s research progression, the aim of this study was to investigate the influence of different playing speeds on muscle activity in the back, upper arm, and forearm in skilled piano playing with a classical music piece. Building upon previous research of novice piano players, we hypothesised that faster tempi elicit higher muscle activity in the forearm of skilled piano players. Additionally, according to previous evidence and findings, we assumed that muscle activity increases in the back and the upper extremity in skilled piano players when the playing tempo rises.

# Method

## Participants

Four female pianists (mean age 30.75 ± 6.34 years) elected to participate in this study after signing the informed consent. All participants were of Asian ethnicity. The average age at which they started playing the piano was 4.5 ± 1 years. All of them received their music education at conservatories as piano majors, and three of them had won prizes at either a national or international competition. The amount of time they practise piano weekly was approximately 23.13 ± 12.48 hours. All participants were right-handed with the laterality index of 97.5 ± 5 according to the Edinburgh Handedness Inventory as shown in Appendix A (Oldfield, 1971). None of them had been diagnosed with any neuromuscular disease. To participant in this study, they had learned and were familiar with the following selected piece: Prelude in C Minor, BWV 847, The Well-Tempered Klavier, Book I, No. 2 (Bach, 1722). Figure 1 shows the first five bars (measures) of the sheet music. The entire piece of music we used in this study can be found in Appendix B.

**Figure 1**

*Excerpt from the Prelude in C Minor, BWV 847*

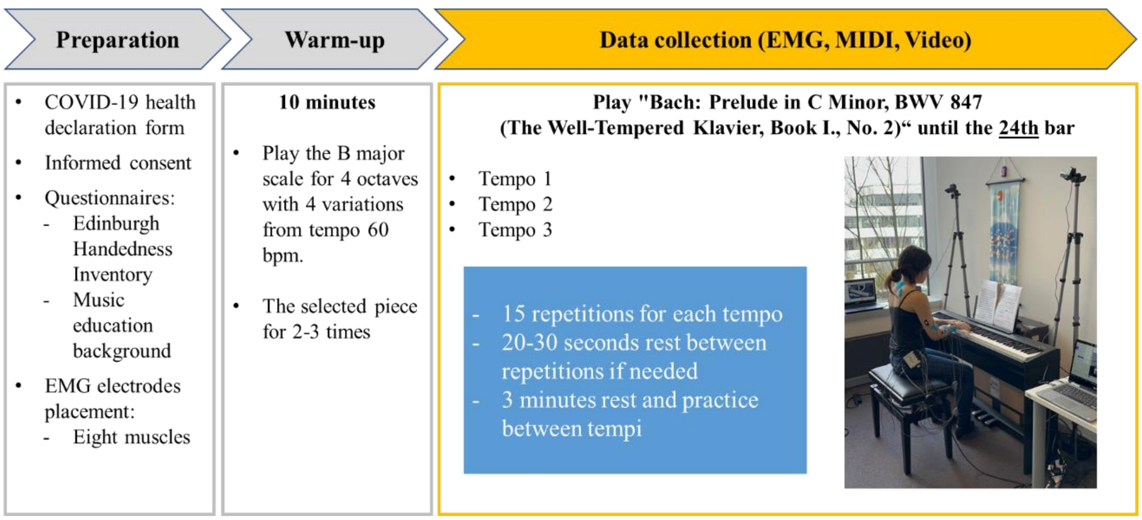

*Note. Allegro vivace* means fast and lively and refers to the recommended playing speed of this piece of music. The tempo marking (♩=144) suggests that the piece should be played ideally at the speed of 144 bpm, when the note value of each beat is a crochet (a quarter note). In general, the notes on the upper stave (the five horizontal lines and the spaces in between) are played with the right hand, and those on the lower stave are played with the left hand. The single vertical lines across the upper and lower staves are bar lines. The treble and bass clef on the right side of the staves indicate higher and lower pitched notes, respectively. The flat symbol (♭) on the staves next to the clefs is the key signature of this piece of music, meaning lower the pitch for the corresponding notes by one semitone. The “C” symbol next to the key signature stands for “common time” and indicates the time signature of this piece of music, meaning that there are four beats per bar, and a crochet represents a beat. With this time signature, four sixteenth notes equal to one crochet and are played on one beat. The natural signs (♮) in the second and the third bar indicates the cancellation of a flat or sharp (♯) from a preceding corresponding note or the key signature. The number above or below a note is the recommended fingering for the players. Each number corresponds to one finger (1 = the thumb, 2 = the index finger, 3 = the middle finger, 4 = the ring finger, 5 = the little finger). The accents (>) and dynamics such as *f* (play loudly or strongly) are ignored during the performance in this study. The version of this sheet music is edited by Carl Czerny (1791-1857).

**Experimental Design and Procedures**

We conducted the experiment with the following procedure: Preparation (questionnaire completion and EMG placement), warm-up, and data collection. These procedures are shown in Figure 2.

**Figure 2**

*Experimental Design of the Study*




*Note.* The two grey and one orange chevrons from the left to the right demonstrate the experimental procedure: preparation (questionnaire completion and EMG placement), warm-up, and data collection, respectively. The three tempi (tempo 1, tempo2, and tempo 3) indicate the first, second, and third playing speeds which were pseudorandomised. The blue box includes the number of repetitions for each playing speed and resting time between repetitions and tempo conditions. The picture displays the posterolateral view from the experimental setup.

***Procedure 1 – Preparation (Questionnaire Completion and EMG Placement)***

The participants were asked to complete the Edinburgh Handedness Inventory (see Appendix A), a self-designed questionnaire regarding music educational background (see Appendix C), and gave permission for the use of photos and film recordings by signing the declaration of consent. They could adjust the height of the piano seat and its distance to the piano to their usual setup. After adjustment, we started placing EMG electrodes on selected muscles according to the following procedure: marking sites, scrubbing, and disinfecting skin, and placing electrodes. Eight muscles from the right side of the back (latissimus dorsi), the right upper arm (triceps brachii lateral head, biceps brachii), and the right forearm (flexor carpi radialis, flexor digitorum superficialis, extensor digitorum, flexor pollicis longus and extensor pollicis longus) were selected. A reference electrode was placed on the surface of the 7$^{th}$ cervical spine as well. The choice of muscles and the corresponding locations of the EMG sensors were based on the SENIAM project (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) and previous studies (Chong et al., 2015; Henseler, Nagels, Nelissen, & de Groot, 2014; Huang et al., 2021; Mohideen & Sidek, 2011; Park & Yoo, 2013).

***Procedure 2 – Warm-Up***

All participants played the B major scale with both hands for four octaves with four additional variations as shown in Appendix D following a metronome from tempo 60 bpm up to 120 bpm several times. It was increased by 10 bpm when the participants felt comfortable with the tempo. After playing the scale, they could choose to play the selected piece two to three times (see Appendix B). The entire warm-up lasted about 10 minutes.

***Procedure 3 – Data Collection***

Participants played the selected piece until the 24$^{th}$ bar at slow (60 bpm), medium (90 bpm) and fast (120 bpm) tempi and 15 times, respectively. The order of the playing tempi was pseudorandomised. Although only the right side of the upper body muscle activity data was gathered, we asked them to perform with both hands in an attempt to have an authentic performing experience. They were asked to follow the fingering on the sheet music and play with *legato* technique, which in terms of playing techniques means that a key is not released until the next keypress. We also asked them to try to play with equal volume, and ignore the dynamics and interpretation. The tempi were given by a metronome during the entire performance. We chose the piece because it is a classical music piece often played and practised by pianists. In addition, the melodic pattern, rhythm, and fingering of this piece are very similar throughout the first 24 bars. Moreover, each of the 24 bar contains the same number of notes for both hands and no rest notation signs. There were 20 to 30 seconds rests between each repetition. And after the last trial of each tempo condition, participants had 3 minutes to take a break and familiarise themselves with the next tempo.

**Data Acquisition**

We used an eight-channel surface electromyography (Delsys - Bagnoli EMG) with a sampling frequency of 1000 Hz to gather the muscle activity data. Participants with attached EMG electrodes played on a digital piano (Roland FP-60, 88 keys) which features weighed keys to mimic the key playing feeling on an acoustic piano. The piano was connected to a Windows computer with MATLAB (R2020a) in order to synchronise the collection of the EMG signals, the MIDI messages, and the time difference in between. We also made video recordings via two webcams (LOGITECH C922 Stream Pro, Fremont, CA, USA) throughout the performances.

**Data Analysis**

MATLAB (R2021a, R2022a) was used to process and analyse the EMG and MIDI data. Instead of time, EMG data was segmented by each bar which contains an equal number of notes throughout the first 24 bars. To identify the start and end of each bar, we transcribed notes on the sheet music to MIDI note numbers (see Appendix E), and wrote codes that enabled MATLAB to recognise the key pressing event of the first right hand note in each bar. The end of each bar was defined as the key pressing event right before the starting key pressing event in the next bar. The end of the 24$^{th}$ bar was defined by the last key pressing event of the entire recording. During this comparison, mistakes made during performances, for instance playing wrong notes, would be revealed as well. A 10$^{th}$ order zero-lag Butterworth bandpass filter with cut off frequencies at 30 and 300 Hz was applied to the EMG data. We also used a notch filter with cut off frequencies at 48 and 52 Hz to eliminate noises from the signals of local powerlines.

The root mean square (RMS) of the EMG data from each bar and each muscle was calculated. To investigate the muscle activities at three different tempi from all participants as a whole, we conducted z-score normalisation by using the means and standard deviations of EMG data based on each participant and each muscle. Furthermore, to confirm if the pianists followed our playing instruction and look into their playing behaviours, we analysed the key pressing velocities for both the right and the left hands.

**Statistical analysis**

Statistical analysis was conducted with the statistical program JASP (version 0.16.3). A one-way repeated measures ANOVA test was used to examine whether there is a difference in means between three different playing speeds of the normalised EMG scores and the key pressing velocities from all participants. Sphericity, which belongs to one of the assumptions of a repeated measures ANOVA test with the null hypothesis that the variances of the differences are equal, was checked by the Mauchly's test. Following that, a Bonferroni post hoc analysis for multiple comparisons was conducted to find out which pair of playing speeds with regards to the means of the normalised EMG scores and the means of the key pressing velocities is statistically different, when the one-way repeated measures ANOVA test rejected its null hypothesis ($p<0.05$).

# Results

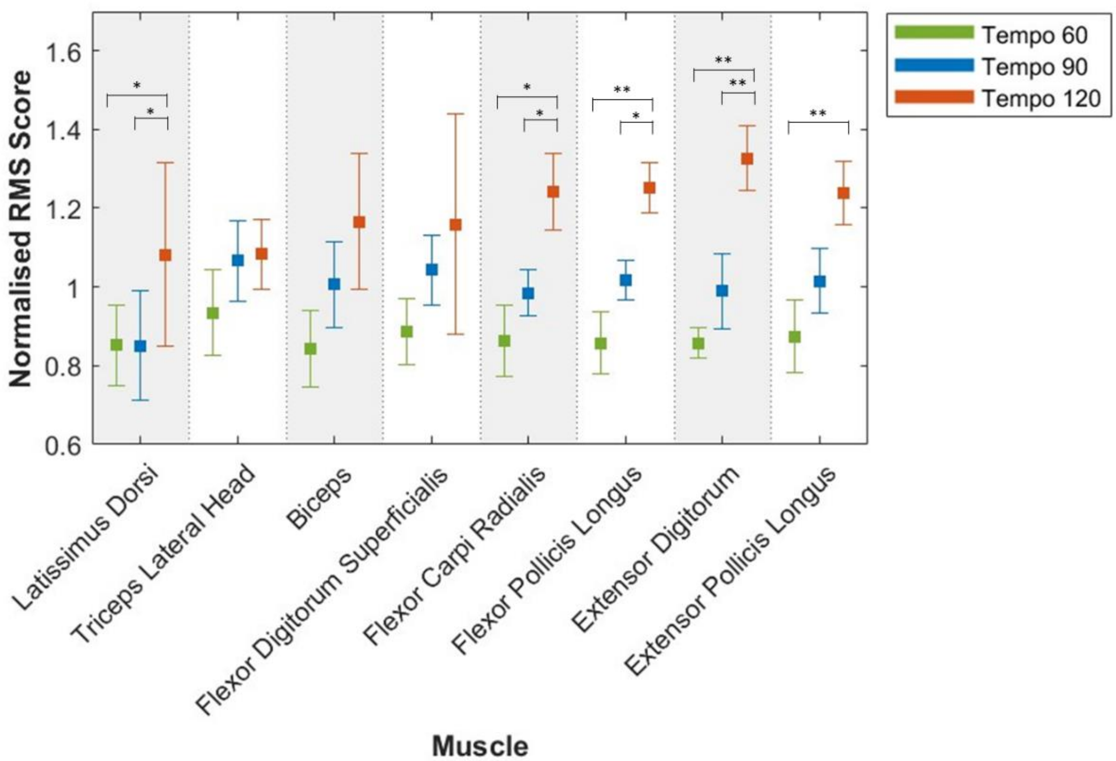
All participants played the selected piece of music at the slow (60 bpm), medium (90 bpm), and fast (120 bpm) tempi 15 times, respectively. Taking into consideration that playing mistakes might occur, and did occur, during the performances and to avoid selection bias, the first seven trials which contained none, or the least amount of playing mistakes, were chosen and analysed.

## EMG Data

Muscle activity in each muscle, from all participants at three different playing speeds, are presented as the mean normalised RMS scores from the EMG data and displayed in Figure 3 and Table 1. All muscles showed the least amount of muscle activity at the slow tempo (60 bpm), whereas the highest amount of activity occurred at the fast tempo (120 bpm). From tempo 60 to 90 bpm, except for the subtle decrease in the mean normalised RMS score in latissimus dorsi, all muscle activity increased. From tempo 90 to 120 bpm, muscle activity in all muscles, apart from the triceps lateral head, demonstrated a relatively substantial upswing. Additionally, the muscle activity increase from tempo 60 to 90 bpm seemed to be proportional if all muscles at one tempo were taken as a whole. Conversely, the muscle activity increase from tempo 90 to 120 bpm did not seem proportional. A one-way repeated measures ANOVA test confirmed that there was a statistically significant difference in the mean normalised RMS scores between at least one pair of different playing speeds for the back muscle (latissimus dorsi) and the four forearm muscles (flexor carpi radialis, flexor pollicis longus, extensor digitorum, and extensor pollicis longus). A following Bonferroni post hoc test for multiple comparisons further identified that the mean normalised RMS scores from the latissimus dorsi, flexor carpi radialis, flexor pollicis longus, and extensor digitorum were not only significantly different between the medium (90 bpm) and fast (120 bpm) tempi, but also the slow (60 bpm) and fast tempi (120 bpm), whereas the extensor pollicis longus only showed a statistically significant difference between tempo 60 and 120 bpm. Counterintuitively, there was no statistically significant difference in any of the muscles' mean normalised RMS scores between tempo 60 and 90 bpm. In addition, despite the incremental increases in muscle activity from the triceps lateral head, biceps, and flexor digitorum superficialis, none of them were proved to be statistically significant different. The results of the one-way repeated measures ANOVA and the post hoc tests are presented in Table 2 and 3, respectively.

**Figure 3**

*Muscle Activity in Each Muscle from All Participants at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each muscle. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants. The square brackets and the star signs indicate the pairs with a statistically significant difference in the mean normalised RMS score.

*$P_{bonf}$ < .05. **$P_{bonf}$ < .01.

**Table 1**

*Means and Standard Deviations of the Normalised RMS Scores in Each Muscle from All Participants at Different Playing Speeds*

| Tempo | Latissimus Dorsi | | Triceps Lateral Head | | Biceps | | Flexor Digitorum Superficialis | | Flexor Carpi Radialis | | Flexor Pollicis Longus | | Extensor Digitorum | | Extensor Pollicis Longus | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Slow | 0.851 | 0.101 | 0.934 | 0.110 | 0.843 | 0.097 | 0.885 | 0.084 | 0.862 | 0.091 | 0.857 | 0.079 | 0.856 | 0.039 | 0.874 | 0.092 |
| Medium | 0.850 | 0.138 | 1.066 | 0.103 | 1.007 | 0.109 | 1.043 | 0.089 | 0.984 | 0.059 | 1.017 | 0.052 | 0.989 | 0.095 | 1.015 | 0.082 |
| Fast | 1.081 | 0.233 | 1.083 | 0.091 | 1.166 | 0.173 | 1.159 | 0.280 | 1.241 | 0.097 | 1.253 | 0.063 | 1.328 | 0.082 | 1.237 | 0.080 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table 2**

*Results of the One-Way Repeated Measures ANOVA Test*

| Muscles | *Case* | *Sphericity Correction* | *Sum of Squares* | *df* | *Mean Square* | *F* | *P* |
|---|---|---|---|---|---|---|---|
| Latissimus dorsi | Tempo | None | 3.408 | 2 | 1.704 | 11.934 | 0.008** |
| Triceps brachii (lateral head) | Tempo | None | 1.282 | 2 | 0.641 | 1.850 | 0.237 |
| Biceps brachii | Tempo | None | 5.027 | 2 | 2.513 | 4.166 | 0.073 |
| Flexor digitorum superficialis | Tempo | None | 3.619 | 2 | 1.809 | 1.773 | 0.248 |
| Flexor carpi radialis | Tempo | None | 7.163 | 2 | 3.581 | 14.683 | 0.005** |
| Flexor pollicis longus | Tempo | None | 7.633 | 2 | 3.817 | 25.758 | 0.001** |
| Extensor digitorum | Tempo | None | 11.345 | 2 | 5.673 | 27.938 | < .001*** |
| Extensor pollicis longus | Tempo | None | 6.454 | 2 | 3.227 | 12.906 | 0.007** |

*Note.* Type III Sum of Squares

*$p$ < .05. **$p$ < .01 ***$p$ < .001

**Table 3**

*Results of the Bonferroni Post Hoc Test*

| Muscles | *Tempo* | | *Mean Difference* | *SE* | *t* | $P_{bonf}$ |
|---|---|---|---|---|---|---|
| Latissimus dorsi | Tempo 60 | Tempo 90 | 8.037e-4 | 0.055 | 0.015 | 1 |
| | | Tempo 120 | -0.23 | 0.055 | -4.224 | 0.017* |
| | Tempo 90 | Tempo 120 | -0.231 | 0.055 | -4.238 | 0.016* |
| Flexor carpi radialis | Tempo 60 | Tempo 90 | -0.122 | 0.071 | -1.709 | 0.415 |
| | | Tempo 120 | -0.378 | 0.071 | -5.308 | 0.005** |
| | Tempo 90 | Tempo 120 | -0.257 | 0.071 | -3.599 | 0.034* |
| Flexor pollicis longus | Tempo 60 | Tempo 90 | -0.161 | 0.056 | -2.892 | 0.083 |
| | | Tempo 120 | -0.396 | 0.056 | -7.135 | 0.001** |
| | Tempo 90 | Tempo 120 | -0.236 | 0.056 | -4.243 | 0.016* |
| Extensor digitorum | Tempo 60 | Tempo 90 | -0.132 | 0.065 | -2.037 | 0.264 |
| | | Tempo 120 | -0.471 | 0.065 | -7.247 | 0.001** |
| | Tempo 90 | Tempo 120 | -0.339 | 0.065 | -5.21 | 0.006** |
| Extensor pollicis longus | Tempo 60 | Tempo 90 | -0.141 | 0.072 | -1.955 | 0.295 |
| | | Tempo 120 | -0.364 | 0.072 | -5.093 | 0.007** |
| | Tempo 90 | Tempo 120 | -0.223 | 0.072 | -3.083 | 0.065 |

*Note.* P-value adjusted for comparing a family of 3

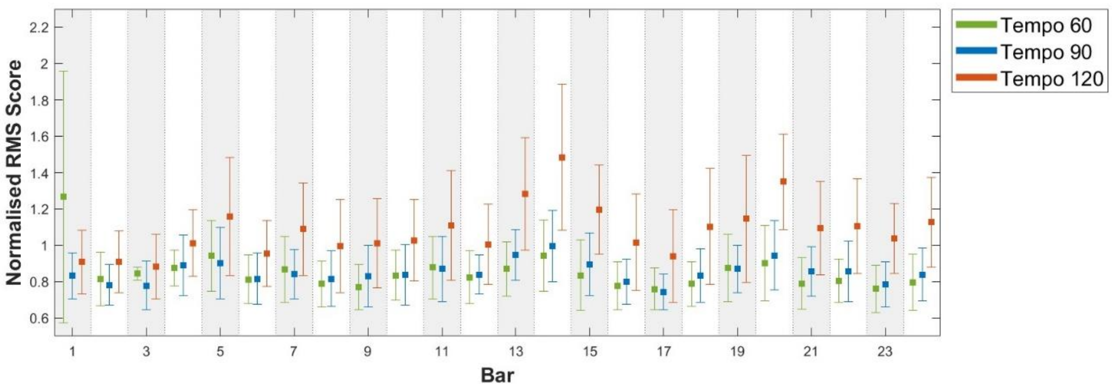
*Note.* Results are averaged over the levels of: Bar

*$p$ < .05. **$p$ < .01.

The following figures (Figure 4, 5, and 6, respectively) display muscle activity from the right latissimus dorsi, biceps, and flexor digitorum superficialis, at three different playing speeds, as examples to show the bar-to-bar progression of muscle activity throughout the entire performance. All individual bar-to-bar muscle activity figures and tables can be found in Appendix F and G, respectively. In general, muscle activity in most of the muscles rose as the playing speed increased. Regardless of the playing speed changes, the bar-to-bar progression of muscle activity remained similar, especially between tempo 60 and 90 bpm. Additionally, many muscles demonstrated a considerable increase in muscle activity in bar 5, 14, 19, and 20.

**Figure 4**

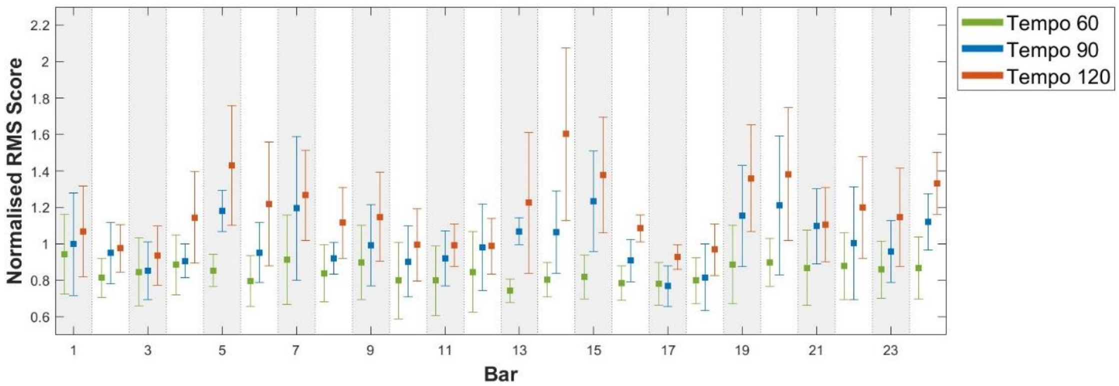
*Bar-to-Bar Muscle Activity in Latissimus Dorsi at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure 5**

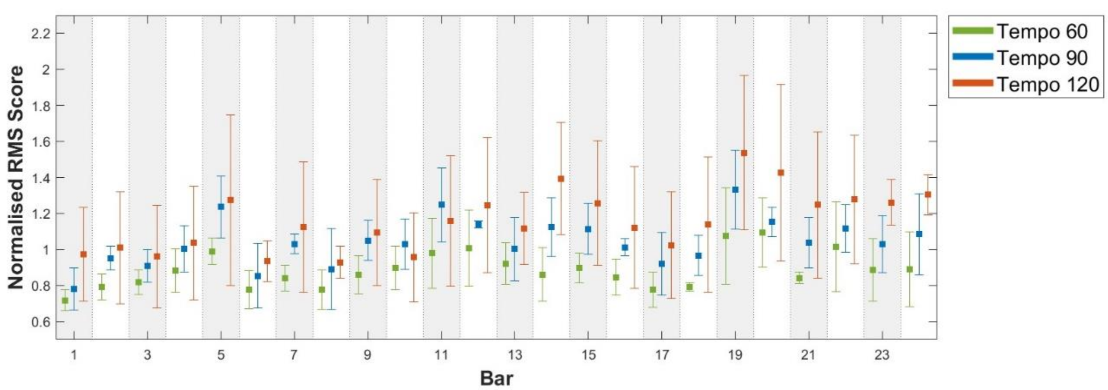
*Bar-to-Bar Muscle Activity in Biceps Brachii at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure 6**

*Bar-to-Bar Muscle Activity in Flexor Digitorum Superficialis at Three Different Playing Speeds*



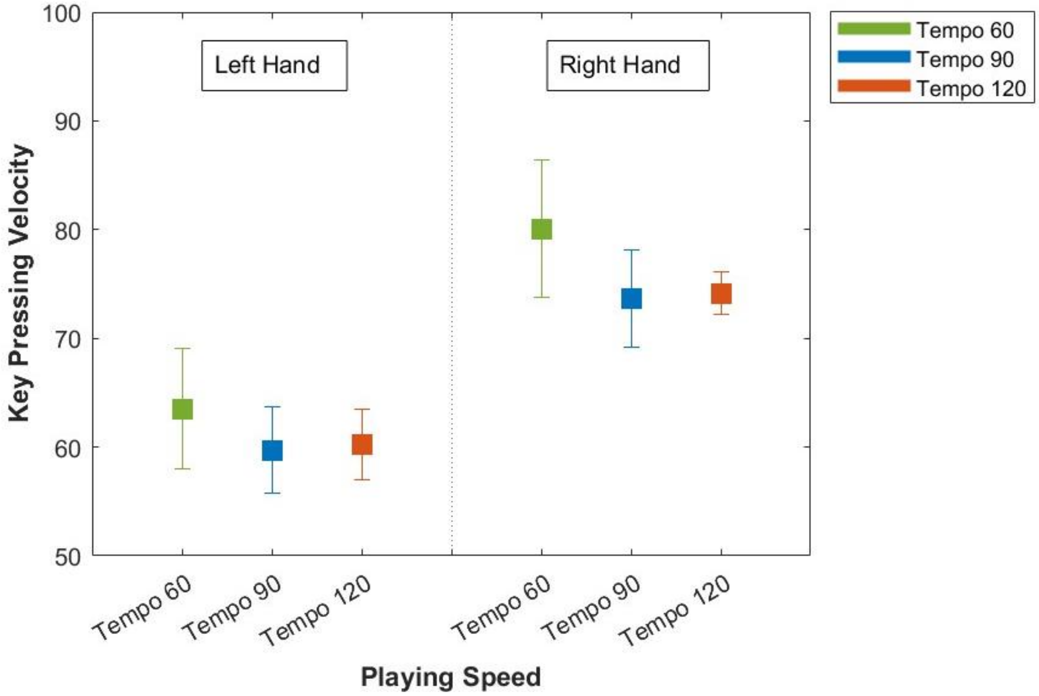

*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Key Pressing Velocity Data**

The average key pressing velocity data at different playing speeds from the left and the right hand is shown in Figure 7. As the figure presents, the average key pressing velocities from the right hand (tempo 60 bpm = 80.08 ± 6.33, tempo 90 bpm = 73.68 ± 4.50, and tempo 120 bpm = 74.13 ± 1.93) are overall higher than those of the left hand (tempo 60 bpm = 63.53 ± 5.58, tempo 90 bpm = 59.71 ± 3.96, and tempo 120 bpm = 60.21 ± 3.22). In both the left and right hands, the slow tempo (60 bpm) has the highest average key pressing velocity throughout the entire performance, and the medium tempo (90 bpm) has the lowest average key pressing velocity. The average key pressing velocity rose slightly as the tempo increased from 90 to 120 bpm. A one-way repeated measures ANOVA test indicated a significant difference in the mean key pressing velocities from the right hand ($F$=5.772, $p$= .04), but not from the left hand ($F$=3.407, $p$= 0.103). Nevertheless, a following Bonferroni post hoc test for multiple comparisons did not identify a statistically significant difference in the mean key pressing velocities between any pair of the tempi.

**Figure 7**

*Average Key Pressing Velocity from the Left and the Right Hand at Three Different Playing Speeds*

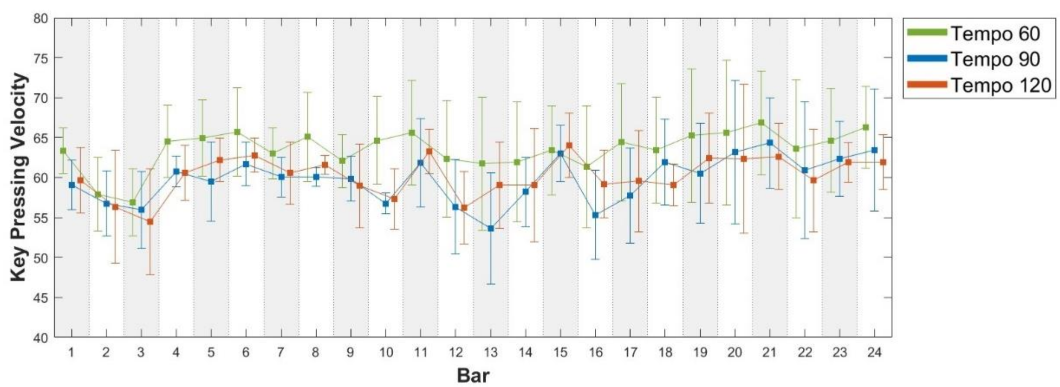



*Note.* The vertical dotted line in the middle is a visual aid to separate the data from the left and the right hands. The key pressing velocity is specified as an integer ranged between 0 and 127 in the MIDI messages and describes how fast or hard a note is played. Each dot represents an average key pressing velocity from the seven trials of all participants. The error bars are derived from the standard deviations and represent the variabilities around the mean from all participants.

The bar-to-bar progression of the average key pressing velocities at different playing speeds from the left and the right hand can be found in Figure 8 and 9, respectively. The corresponding key pressing velocity' values are also displayed in Appendix H. The left hand demonstrated the highest average key pressing velocity at tempo 60 bpm in most of the bars. The difference among the three tempi is, however, not very distinguishable, especially between tempo 90 and 120 bpm. On the other hand, the right hand displayed the highest average key pressing velocities throughout all the 24 bars at the slow tempo (60 bpm). Nevertheless, the occurrence of higher key pressing velocities between the medium (90 bpm) and fast tempi (120 bpm) altered often from bar to bar. Regardless of the playing speed changes, the overall progression in key pressing velocity from the right hand remained similar from bar one to bar 24.

**Figure 8**

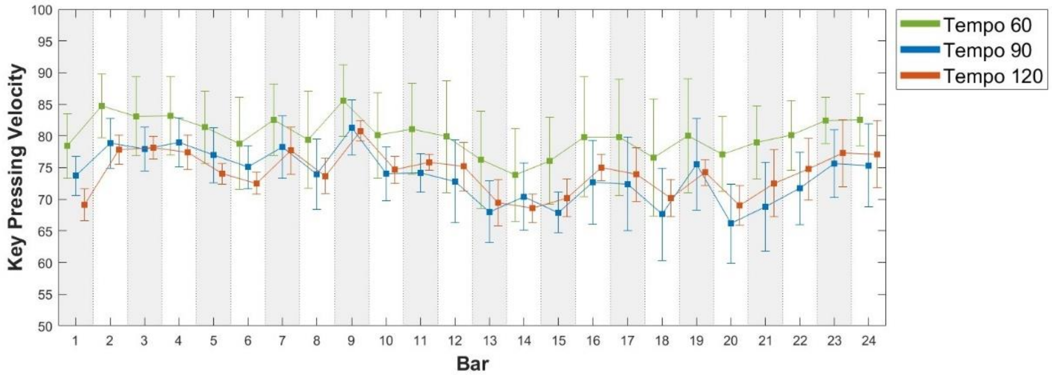
*Bar-to-Bar Average Key-Pressing Velocities from the Left Hand at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. The key pressing velocity is specified as an integer ranged between 0 and 127 in the MIDI messages and describes how fast or hard a note is played. Each dot represents an average key pressing velocity from the seven trials of all participants. The error bars are derived from the standard deviations and represent the variabilities around the mean from all participants.

**Figure 9**

*Bar-to-Bar Average Key-Pressing Velocities from the Right Hand at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. The key pressing velocity is specified as an integer ranged between 0 and 127 in the MIDI messages and describes how fast or hard a note is played. Each dot represents an average key pressing velocity from the seven trials of all participants. The error bars are derived from the standard deviations and represent the variabilities around the mean from all participants.

## Discussion

This study’s aim was to investigate the influence of different playing speeds on muscle activity in the back, upper arm, and forearm in skilled piano playing with a classical music piece. Our results showed the least amount of muscle activity at the slow tempo (60 bpm), and the highest amount of activity at the fast tempo (120 bpm). From tempo 60 to 90 bpm, except for the subtle decrease in the mean normalised RMS score in latissimus dorsi, all muscle activity increased. From tempo 90 to 120 bpm, muscle activity in all muscles other than triceps lateral head demonstrated a relatively substantial upswing. Furthermore, the difference in muscle activity between medium (90 bpm) and fast tempi (120 bpm) were confirmed to be statistically significant in the latissimus dorsi, flexor carpi radialis, flexor pollicis longus, and extensor digitorum. Between tempo 60 and 120 bpm, statistically significant difference was also identified not only in the aforesaid four muscles, but also in the extensor pollicis longus. Counterintuitively, there was no statistically difference in any of the muscles’ mean normalised RMS scores between the slow (60 bpm) and medium (90 bpm) tempi. Additionally, despite the incremental increases in muscle activity from the upper arm (biceps brachii and triceps lateral head) and the finger flexor (flexor digitorum superficialis), we did not observe a statistically significant difference as the tempo rose.

Our first hypothesis regarding faster playing speeds elicit higher muscle activity in the forearm of skilled piano players was partially supported, since not all muscles examined in the forearm had statistically higher activities at the medium and fast tempi (90 and 120 bpm, respectively), compared to the activity at the slow tempo (60 bpm). These results are, however, different from the previous study in which an overall statistically significant increase was observed in the forearm’s muscle activity, except for the flexor carpi radialis (Chong et al., 2015). There are a few grounds which may account for the differences. Firstly, the study from Chong et al. was conducted with participants who reported less than three years’ keyboard-related playing experience and had received no professional music education within the past 10 years. Research findings in the past, however, have identified apparent differences in kinematic analysis and muscle activity between expert pianists and novice or recreational piano players (S. Furuya, Goda, et al., 2011; S. Furuya & Kinoshita, 2007; Shinichi Furuya & Kinoshita, 2008). Therefore, these different observations in regard to muscle activity in the forearm may stem from the difference in experience and level of proficiency in piano playing. Secondly, the piano playing tasks in the study above were only composed of five adjacent notes in assigned sequences. Conversely, ours consisted of 24 bars from a classical music piece, and contained wider and various ranges of intervals. These require not only more parallel movements from the fingers and wrists, but also more skilled playing such as different combinations of finger movement sequences. The differences in the level of task difficulty and movement requirements could also cause different outcomes. Thirdly, whilst the aforementioned study compared the muscle activities between a self-paced tempo condition with the interkeystroke interval (IKI) around 750 ms and a fast-paced tempo condition in which the participants played as fast as possible (IKI ~ 200 ms), we conducted our study with three pre-defined playing speeds (60 bpm or IKI 250 ms, 90 bpm or IKI 167 ms, and 120 bpm or 125 ms) with noticeable increase, substantial faster playing speeds in general, and the potential to play at an even faster tempo. Fourthly, our study consisted of very limited participants, and this may have an impact on the statistical analysis due to the small sample size. Furthermore, the aforesaid study was with male participants and ours was with female pianists. Whether there is a gender effect in terms of muscle activities in piano playing has not yet been proven, and this could cause different results as well.

Our second hypothesis regarding the increase of the muscle activity in the back and upper arm as the tempo rises was partially supported as well. Previous studies stated that expert pianist started the key pressing task with a substantial shoulder flexion, leading to a greater key pressing angle. Additionally, from the finger-key contact moment till the key was fully pressed, more shoulder flexion and elbow extension were observed (S. Furuya, Goda, et al., 2011; S. Furuya & Kinoshita, 2007; Shinichi Furuya & Kinoshita, 2008). In our study, however, despite the incremental increases in muscle activity in biceps brachii and triceps lateral head in response to faster playing speeds, these differences were not statistically significant. We reasoned that the cause could be the different uses of the playing techniques. In the abovementioned studies, participants were asked to apply the *staccato* technique, requiring players to play each note shortly and separately from the note before and after. As a result, more active movements from the wrists and even elbows or upper arms may be involved. Participants in our study, conversely, were asked to play with the completely opposite technique (*legato*) throughout the entire performance. Moreover, the previous studies measured not only the biceps and triceps muscles, but also the deltoid muscles to investigate the shoulder joint movements. Due to the scope of this study, we did not examine those muscles.

Nevertheless, one strength of this study is that we extended the examination of muscle activity from the upper limb to the back. We confirmed that the back muscle activity (latissimus dorsi) increased at both medium and fast tempi compared to that at the slow playing speed. In the past, kinematic and muscle activity data concentrated more on the upper extremities but not the back or the trunk. However, since we observed a small contribution of the latissimus dorsi muscle in our former case-study regarding a downward ball-throwing intervention to induce the proximal-to-distal sequencing of the upper extremity in piano playing, we decided to include this muscle in the present study (Huang et al., 2021). Moreover, this finding is also in line with a recent study, regarding trunk and hand coordination, in which a greater trunk range of motion was observed when pianists played faster (Turner, Visentin, Oye, Rathwell, & Shan, 2022). It also pointed out the importance of anthropometry in the proximal-to-distal preparatory strategy in piano performance.

One interesting finding in our study is that even with an obvious increase from each tempo condition to another, a statistically significant difference in muscle activity was solely identified between tempo 90 and 120 bpm in some muscles. Counterintuitively, we observed no statistically significant difference in all muscle activities between tempo 60 and 90 bpm. This may indicate that pianists are capable of performing at a range of different playing speeds without increasing their muscle activities. This could also be associated with previous evidence regarding spatial and temporal symmetries of movement in skilled piano performance, suggesting that the nervous system can produce a wide range of movement repertoires from a small set of motor primitives (van Vugt et al., 2014). One the other hand, unlike playing at the slow tempo, the occurrence of higher muscle activities at the medium and fast tempi could also be a response from the neuromuscular system, indicating that a different motor behaviour may be required. Since most of the muscles examined in this study were pairs of agonist and antagonist muscles, the overall increase in muscle activity as the tempo rose could also be a sign of higher demand for joint stiffness or co-contraction of the muscles as previous studies discovered (S. Furuya, Goda, et al., 2011; S. Furuya & Kinoshita, 2007). However, the analysis of co-contraction requires an even smaller time window than a bar. Due to the scope of this work, we did not include related analysis.

In an attempt to look into participants' playing behaviour and reason about possible mechanisms influencing pianists' ability to perform at fast speeds, we analysed the key pressing velocities from each note saved in the MIDI messages. The key pressing velocity in the MIDI messages describes how fast or hard a note is played. A one-way repeated measures ANOVA test indicated a statically significant difference in the mean key-pressing velocities at different tempi on the right hand, but not on the left hand. The significant level from the statistics on the right hand was, however, too low for the following Bonferroni analysis to identify a statistical difference between any pair of the tempi. Even a less conservative Holm post hoc test did not find any statistically significant pairs. In addition, the increase or decrease of the key pressing velocities in response to different playing speeds, was not in line with our findings in muscle activity. Therefore, pressing keys harder or faster while playing the piano may not be an explanation of pianists' ability to perform at considerable speeds. From this data, we could also confirm that the participants followed the playing instructions to play the entire performance with as close to an even volume as possible. Nevertheless, regardless of the difference in the average key pressing velocity at different playing tempi, we also noticed an overall lower average key pressing velocity from the left hand. This may be influenced by the arrangement of melody and accompaniment in the selected music (and most classical music pieces): the main melody is on the right hand and the accompaniment is on the left hand. As a result, when we asked the pianists to play with equal volume, they might subconsciously apply different force to their left and right hand to achieve a harmonic performance.

Another assumption in regard to pianists' ability to play fast is the change of muscle synergies at different tempi, namely, whether the contribution of muscle activity from each muscle in piano playing alters as the playing speed changes. As the Figure 4, 5, 6 and figures in Appendix F present, the bar-to-bar progression of each muscle' activity seemed to remain similar throughout the entire performance regardless how fast or how slow the participants played the piano. This observation could be related to the previous findings in kinematic analysis, displaying that the contributions of each individual joint remained similar across different tempi (Goebl & Palmer, 2013). Additionally, former studies also suggested that various combination of a small number of muscle synergies can be shared across different behaviours (Chvatal & Ting, 2013; D'avella & Lacquaniti, 2013). However, if the muscle synergies did not change across different playing speeds, we should have observed in Figure 3 an overall proportional increase in muscle activity not only from tempo 60 to 90 bpm, but also from 90 to 120 bpm. This observation could indicate that similar muscle synergies could be used across a range of different playing speeds. However, beyond this range of playing speeds, a change in muscle synergies may occur.

Another interesting finding regarding the bar-to-bar progression of each muscle' activity is the considerable increases in the mean normalised RMS scores in bar 5, 14, 19, and 20 across many muscles. After comparing the playing behaviours such as the fingering, finger and wrist positions, movement sequences and so forth in those bars with other bars, we proposed some possible explanations. From the beginning of the music till the fourth bar, the distance between notes and the transitions from bar to bar on the right hand were relatively small and did not cross a wide range of intervals. Therefore, pianists could easily play through those bars with a neutral wrist position. However, moving from the last two notes of the fourth bar to the first note of the fifth bar, the fingering on the sheet music required pianists to cross their thumb under the index finger, then reached the first note of the fifth bar, which is a black key, with their little finger. In order to hit the key precisely and make the note as equal loud as the other notes with the little finger, more wrist and forearm movements such as supination may be involved. In addition, the impact of the thumb-under manoeuvre in piano playing has also been revealed in other studies (S. Furuya, Flanders, et al., 2011; van Vugt et al., 2014). Inspecting the sheet music from the first to the 13th bar, we noticed that there were at most two black keys in a bar. However, three black keys were composed in the 14th bar. Since the black keys are located upper and higher than the white keys, this could make pianists adopt a higher wrist position. Besides, to reach the lowest two keys with the thumb and index finger as the fingering indicated in this bar, pianists may have to leave their neutral wrist position and perform more ulnar deviation. In the 19th and 20th bar, the distance between the lowest and highest keys on the keyboard were relatively bigger than those in other bars. To cover the distance, pianists had to move their wrist back and forth from radial to ulnar deviations.

Two more strengths were displayed in this study. Firstly, most research in the past in piano playing we mentioned used simpler finger movement sequences or shorter melodies and focused on unilateral performance. This setting was, however, far from an authentic piano playing experience, especially for experts or experienced piano players. In order to reproduce an authentic playing experience and meanwhile enable the data collection of the MIDI messages while performing, we selected not only a digital piano which features weighed keys, but also a classical music piece which is well-known and commonly seen in musicians’ repertoire. Furthermore, despite the fact that only the right-side muscles were measured, as the influence of the back muscle and the importance of trunk movement in piano playing has been observed, we asked our participants to play with both hands (Huang et al., 2021; Turner et al., 2022). This also made the entire data colleting procedure closer to an authentic performing situation. Secondly, the collection of the MIDI and EMG data was synchronised. Therefore, instead of using time to segment EMG data, we were able to precisely identify where did a bar start and stop. This allowed us to perform the analysis not only for the entire performance, but also for each bar.

There are some more limitations of this study. Firstly, the participants in this study were coincidentally all female and of Asian ethnicity. Whether our research findings are applicable to other genders and people of different ethnicities remains uncertain. Secondly, even though there was a guidance in fingering on the sheet music, it is not provided for every single note, and we did not check if all participants played with identical fingering. Thirdly, due to the melodic pattern and suitable fingering while performing, the use of the ring finger was drastically less than other fingers. Therefore, the finger movement sequences used in this study were limited and did not cover various variations. Fourthly, even though each tempo condition was performed 15 times, we only used seven trials which contained none, or the least amount of playing mistakes in the analysis. Finally, since this study was conducted with surface EMG and most forearm muscles are very close to one another or have a certain degree of overlaps, crosstalk of EMG signals from different muscles was inevitable.

Even though the present study observed that skilled pianists' muscle activity from the back, upper arm, and forearm increased in piano playing with a classical music piece, our two hypotheses regarding faster playing speeds elicit higher muscle activity were partially supported since not all increases were proved to be statistically significant. With the intension of finding out how pianists play at considerable speeds, we included the analysis of the key pressing velocity. The results suggest that pianists' ability to perform at fast tempi may not account for how fast or hard they hit or press the keys while playing the piano. Additionally, according to previous literature and our results from the muscle activity data, we suppose that pianists could be capable of performing at a range of different speeds without increasing their muscle activities. However, beyond this range of playing speeds, a different motor behaviour may be required in order to respond to a higher demand from the neuromuscular system. This study not only lays the groundwork for investigating muscle activity in piano playing at a higher level of proficiency, but also suggests various aspects and factors which could be taken into consideration. Future studies could focus on muscle synergies and co-contractions in response to different playing speeds to further explore the mechanisms of pianists' ability to play at fast tempi.

**References**


Bach, J. S. (1722). Das wohltemperierte Klavier.

Bove, M., Tacchino, A., Novellino, A., Trompetto, C., Abbruzzese, G., & Ghilardi, M. F. (2007). The effects of rate and sequence complexity on repetitive finger movements. *Brain Research, 1153*, 84-91. doi:https://doi.org/10.1016/j.brainres.2007.03.063

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*. doi:10.3389/fpsyg.2015.01277

Chvatal, S., & Ting, L. (2013). Common muscle synergies for balance and walking. *Frontiers in Computational Neuroscience, 7*. doi:10.3389/fncom.2013.00048

D'avella, A., & Lacquaniti, F. (2013). Control of reaching movements by muscle synergy combinations. *Frontiers in Computational Neuroscience, 7*. doi:10.3389/fncom.2013.00042

Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: evidence of maximal adaptation to task constraints. *Annu Rev Psychol, 47*, 273-305. doi:10.1146/annurev.psych.47.1.273

Furuya, S., Flanders, M., & Soechting, J. F. (2011). Hand kinematics of piano playing. *J Neurophysiol, 106*(6), 2849-2864. doi:10.1152/jn.00378.2011

Furuya, S., Goda, T., Katayose, H., Miwa, H., & Nagata, N. (2011). Distinct Inter-Joint Coordination during Fast Alternate Keystrokes in Pianists with Superior Skill. *Front Hum Neurosci, 5*, 50. doi:10.3389/fnhum.2011.00050

Furuya, S., & Kinoshita, H. (2007). Roles of proximal-to-distal sequential organization of the upper limb segments in striking the keys by expert pianists. *Neurosci Lett, 421*(3), 264-269. doi:10.1016/j.neulet.2007.05.051

Furuya, S., & Kinoshita, H. (2008). Organization of the upper limb movement for piano key-depression differs between expert pianists and novice players. *Experimental Brain Research, 185*(4), 581-593. doi:10.1007/s00221-007-1184-9

Furuya, S., & Soechting, J. F. (2012). Speed invariance of independent control of finger movements in pianists. *J Neurophysiol, 108*(7), 2060-2068. doi:10.1152/jn.00378.2012

Goebl, W., & Palmer, C. (2013). Temporal control and hand movement efficiency in skilled music performance. *PLoS One, 8*(1), e50901. doi:10.1371/journal.pone.0050901

Henseler, J. F., Nagels, J., Nelissen, R. G. H. H., & de Groot, J. H. (2014). Does the latissimus dorsi tendon transfer for massive rotator cuff tears remain active postoperatively and restore active external rotation? *Journal of Shoulder and Elbow Surgery, 23*(4), 553-560. doi:10.1016/j.jse.2013.07.055

Hirano, M., Kimoto, Y., & Furuya, S. (2020). Specialized Somatosensory-Motor Integration Functions in Musicians. *Cereb Cortex, 30*(3), 1148-1158. doi:10.1093/cercor/bhz154

Huang, H., Forano, M., & Franklin, D. (2021). *Changes in Volume, Dynamic Range and Music Activity - Piano Playing After a Ball Throwing Intervention*. Paper presented at the Art in Motion, Munich, Germany.

Mohideen, A. J. H., & Sidek, S. N. (2011, 17-19 May 2011). *Development of EMG circuit to study the relationship between flexor digitorum superficialis muscle activity and hand grip strength.* Paper presented at the 2011 4th International Conference on Mechatronics (ICOM).

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113. doi:10.1016/0028-3932(71)90067-4

Park, S.-y., & Yoo, W.-g. (2013). Selective activation of the latissimus dorsi and the inferior fibers of trapezius at various shoulder angles during isometric pull-down exertion. *Journal of Electromyography and Kinesiology, 23*(6), 1350-1355. doi:https://doi.org/10.1016/j.jelekin.2013.08.006

Turner, C., Visentin, P., Oye, D., Rathwell, S., & Shan, G. (2022). An Examination of Trunk and Right-Hand Coordination in Piano Performance: A Case Comparison of Three Pianists. *Front Psychol, 13,* 838554. doi:10.3389/fpsyg.2022.838554

van Vugt, F. T., Furuya, S., Vauth, H., Jabusch, H.-C., & Altenmüller, E. (2014). Playing beautifully when you have to be fast: spatial and temporal symmetries of movement patterns in skilled piano performance at different tempi. *Experimental Brain Research, 232*(11), 3555-3567. doi:10.1007/s00221-014-4036-4

# Appendix A

## Edinburgh Handedness Inventory

Please indicate your preferences in the use of hands in the following activities. If you are really indifferent, select "Either".

| | Left | Either | Right |
|---|---|---|---|
| Writing | | | |
| Drawing | | | |
| Throwing | | | |
| Using Scissors | | | |
| Using a toothbrush | | | |
| Using a knife (without a fork) | | | |
| Using a spoon | | | |
| Using a broom (upper hand) | | | |
| Striking a match (match) | | | |
| Opening a box (lid) | | | |

## Appendix B

## Prelude in C Minor, BWV 847, The Well-Tempered Klavier, Book I, No. 2


*Note.* Only the first 24 bars were used in this study. Editor: Carl Czerny (1791-1857)

# Appendix C

## Music Education Background Questionnaire

Your birth year: __________

1. Do you practise / play the piano regularly?

☐ Yes
☐ No (please jump to question 8 on the next side)

2. Are you a conservatory student?

☐ Yes, at ______________________________ since ____________

Major instrument ____________________, minor instrument ____________________

☐ No. I've received my piano education at/from ___________________ since __________

3. Have you ever won a national or international piano competition?

☐ Yes
☐ No

4. At what age did you start playing the piano?

When I was _____ years old.

5. Have there ever been a pause since your started learning the piano?

☐ Yes, ____________________ (how long)
☐ No

6. How often do you practise / play the piano?

_____ time(s) per day

_____ time(s) per week

_____ time(s) per month

Other: _____

7. How much time do you spend on each practise / playing session?

_____ hour(s) _____ minutes

8. When did you learn the piano?

From __________ to __________

9. Were you a conservatory student?

☐ Yes, at _____________________________ from _____ to _____

Major instrument ____________________, minor instrument ____________________

☐ No. I've received my piano education at/from ___________________ since __________

10. Have you ever won a national or international piano competition?

☐ Yes
☐ No

11. How often did you practise / play the piano?

_____ time(s) per day

_____ time(s) per week

_____ time(s) per month

Other: _____

12. How much time did you spend on each practise / playing session?

_____ hour(s) _____ minutes

# Appendix D

## B Major Scale and Four Variations

B Major Scale


Variation 1

Variation 2

Variation 3

Variation 4

# Appendix E

## Transcription of the MIDI Note Numbers of the First 24 Bars of the Prelude in C Minor, BWV 847

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Bar 1** | | | | | | | | | | | | | | | | **Bar 2** | | | | | | | | | | | | | | | |
| **Right Hand** | 72 | 63 | 62 | 63 | 60 | 63 | 62 | 63 | 72 | 63 | 62 | 63 | 60 | 63 | 62 | 63 | 68 | 65 | 64 | 65 | 60 | 65 | 64 | 65 | 68 | 65 | 64 | 65 | 60 | 65 | 64 | 65 |
| **Left Hand** | 48 | 55 | 53 | 55 | 51 | 55 | 53 | 55 | 48 | 55 | 53 | 55 | 51 | 55 | 53 | 55 | 48 | 56 | 55 | 56 | 53 | 56 | 55 | 56 | 48 | 56 | 55 | 56 | 53 | 56 | 55 | 56 |
| | **Bar 3** | | | | | | | | | | | | | | | | **Bar 4** | | | | | | | | | | | | | | | |
| **Right Hand** | 71 | 65 | 63 | 65 | 62 | 65 | 63 | 65 | 71 | 65 | 63 | 65 | 62 | 65 | 63 | 65 | 72 | 67 | 65 | 67 | 63 | 67 | 65 | 67 | 72 | 67 | 65 | 67 | 63 | 67 | 65 | 67 |
| **Left Hand** | 48 | 56 | 55 | 56 | 53 | 56 | 55 | 56 | 48 | 56 | 55 | 56 | 53 | 56 | 55 | 56 | 48 | 51 | 50 | 51 | 55 | 51 | 50 | 51 | 48 | 51 | 50 | 51 | 55 | 51 | 50 | 51 |
| | **Bar 5** | | | | | | | | | | | | | | | | **Bar 6** | | | | | | | | | | | | | | | |
| **Right Hand** | 75 | 68 | 67 | 68 | 63 | 68 | 67 | 68 | 75 | 68 | 67 | 68 | 63 | 68 | 67 | 68 | 74 | 66 | 64 | 66 | 62 | 66 | 64 | 66 | 74 | 66 | 64 | 66 | 62 | 66 | 64 | 66 |
| **Left Hand** | 48 | 60 | 58 | 60 | 56 | 60 | 58 | 60 | 48 | 60 | 58 | 60 | 56 | 60 | 58 | 60 | 48 | 57 | 55 | 57 | 54 | 57 | 55 | 57 | 48 | 57 | 55 | 57 | 54 | 57 | 55 | 57 |
| | **Bar 7** | | | | | | | | | | | | | | | | **Bar 8** | | | | | | | | | | | | | | | |
| **Right Hand** | 74 | 67 | 66 | 67 | 62 | 67 | 66 | 67 | 74 | 67 | 66 | 67 | 62 | 67 | 66 | 67 | 72 | 64 | 62 | 64 | 60 | 64 | 62 | 64 | 72 | 64 | 62 | 64 | 60 | 64 | 62 | 64 |
| **Left Hand** | 46 | 58 | 57 | 58 | 55 | 58 | 57 | 58 | 46 | 58 | 57 | 58 | 55 | 58 | 57 | 58 | 46 | 55 | 53 | 55 | 52 | 55 | 53 | 55 | 46 | 55 | 53 | 55 | 52 | 55 | 53 | 55 |
| | **Bar 9** | | | | | | | | | | | | | | | | **Bar 10** | | | | | | | | | | | | | | | |
| **Right Hand** | 72 | 65 | 64 | 65 | 60 | 65 | 64 | 65 | 72 | 65 | 64 | 65 | 60 | 65 | 64 | 65 | 70 | 65 | 63 | 65 | 62 | 65 | 63 | 65 | 70 | 65 | 63 | 65 | 62 | 65 | 63 | 65 |
| **Left Hand** | 44 | 56 | 55 | 56 | 53 | 56 | 55 | 56 | 44 | 56 | 55 | 56 | 53 | 56 | 55 | 56 | 44 | 50 | 48 | 50 | 53 | 50 | 48 | 50 | 44 | 50 | 48 | 50 | 53 | 50 | 48 | 50 |
| | **Bar 11** | | | | | | | | | | | | | | | | **Bar 12** | | | | | | | | | | | | | | | |
| **Right Hand** | 70 | 67 | 65 | 67 | 63 | 67 | 65 | 67 | 70 | 67 | 65 | 67 | 63 | 67 | 65 | 67 | 68 | 67 | 65 | 67 | 63 | 67 | 65 | 67 | 68 | 67 | 65 | 67 | 63 | 67 | 65 | 67 |
| **Left Hand** | 43 | 51 | 50 | 51 | 55 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 55 | 51 | 50 | 51 | 48 | 51 | 50 | 51 | 56 | 51 | 50 | 51 | 48 | 51 | 50 | 51 | 56 | 51 | 50 | 51 |
| | **Bar 13** | | | | | | | | | | | | | | | | **Bar 14** | | | | | | | | | | | | | | | |
| **Right Hand** | 68 | 62 | 60 | 62 | 58 | 62 | 60 | 62 | 68 | 62 | 60 | 62 | 58 | 62 | 60 | 62 | 67 | 58 | 56 | 58 | 63 | 58 | 56 | 58 | 67 | 58 | 56 | 58 | 63 | 58 | 56 | 58 |
| **Left Hand** | 50 | 53 | 51 | 53 | 56 | 53 | 51 | 53 | 50 | 53 | 51 | 53 | 56 | 53 | 51 | 53 | 51 | 55 | 53 | 55 | 56 | 55 | 53 | 55 | 51 | 55 | 53 | 55 | 56 | 55 | 53 | 55 |
| | **Bar 15** | | | | | | | | | | | | | | | | **Bar 16** | | | | | | | | | | | | | | | |
| **Right Hand** | 65 | 60 | 58 | 60 | 57 | 60 | 58 | 60 | 65 | 60 | 58 | 60 | 57 | 60 | 58 | 60 | 65 | 62 | 60 | 62 | 59 | 62 | 60 | 62 | 65 | 62 | 60 | 62 | 59 | 62 | 60 | 62 |
| **Left Hand** | 51 | 57 | 55 | 57 | 53 | 57 | 55 | 57 | 51 | 57 | 55 | 57 | 53 | 57 | 55 | 57 | 50 | 53 | 51 | 53 | 56 | 53 | 51 | 53 | 50 | 53 | 51 | 53 | 56 | 53 | 51 | 53 |
| | **Bar 17** | | | | | | | | | | | | | | | | **Bar 18** | | | | | | | | | | | | | | | |
| **Right Hand** | 65 | 62 | 60 | 62 | 59 | 62 | 60 | 62 | 65 | 62 | 60 | 62 | 59 | 62 | 60 | 62 | 63 | 60 | 59 | 60 | 55 | 60 | 59 | 60 | 63 | 60 | 59 | 60 | 55 | 60 | 59 | 60 |
| **Left Hand** | 48 | 53 | 52 | 53 | 56 | 53 | 52 | 53 | 48 | 53 | 52 | 53 | 56 | 53 | 52 | 53 | 48 | 51 | 50 | 51 | 53 | 51 | 50 | 51 | 46 | 51 | 50 | 51 | 53 | 51 | 50 | 51 |
| | **Bar 19** | | | | | | | | | | | | | | | | **Bar 20** | | | | | | | | | | | | | | | |
| **Right Hand** | 53 | 63 | 62 | 63 | 65 | 63 | 62 | 63 | 53 | 63 | 62 | 63 | 65 | 63 | 62 | 63 | 54 | 60 | 59 | 60 | 63 | 60 | 59 | 60 | 54 | 60 | 59 | 60 | 63 | 60 | 59 | 60 |
| **Left Hand** | 44 | 48 | 47 | 48 | 50 | 48 | 47 | 48 | 44 | 48 | 47 | 48 | 50 | 48 | 47 | 48 | 45 | 51 | 50 | 51 | 48 | 51 | 50 | 51 | 45 | 51 | 50 | 51 | 48 | 51 | 50 | 51 |
| | **Bar 21** | | | | | | | | | | | | | | | | **Bar 22** | | | | | | | | | | | | | | | |
| **Right Hand** | 63 | 60 | 59 | 60 | 55 | 60 | 59 | 60 | 63 | 60 | 59 | 60 | 55 | 60 | 59 | 60 | 66 | 60 | 59 | 60 | 57 | 60 | 59 | 60 | 66 | 60 | 59 | 60 | 57 | 60 | 59 | 60 |
| **Left Hand** | 43 | 51 | 50 | 51 | 53 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 53 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 48 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 48 | 51 | 50 | 51 |
| | **Bar 23** | | | | | | | | | | | | | | | | **Bar 24** | | | | | | | | | | | | | | | |
| **Right Hand** | 67 | 60 | 59 | 60 | 62 | 60 | 59 | 60 | 67 | 60 | 59 | 60 | 62 | 60 | 59 | 60 | 68 | 60 | 59 | 60 | 62 | 60 | 59 | 60 | 68 | 60 | 59 | 60 | 62 | 60 | 59 | 60 |
| **Left Hand** | 43 | 51 | 50 | 51 | 53 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 53 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 53 | 51 | 50 | 51 | 43 | 51 | 50 | 51 | 53 | 51 | 50 | 51 |

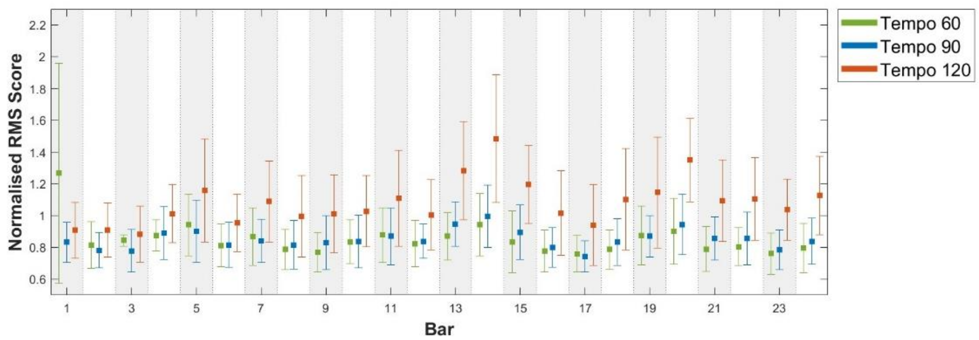
*Note.* MIDI note numbers are specified as integers ranged between 0 to 127. The MIDI note number of the Middle C is 60.

## Appendix F

## Bar-to-Bar Muscle Activity in Each Muscle at Three Different Playing Speeds

**Figure F1**

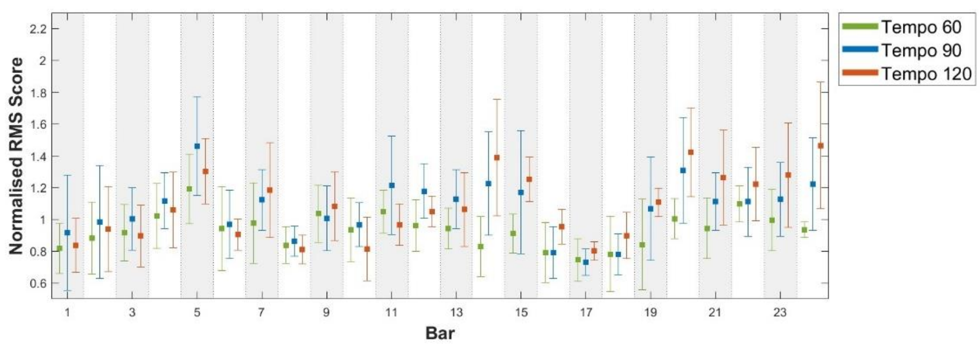
*Bar-to-Bar Muscle Activity in Latissimus Dorsi at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F2**

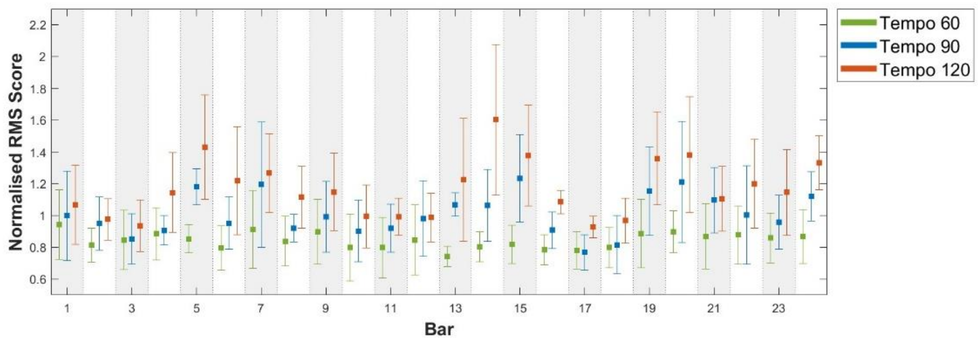
*Bar-to-Bar Muscle Activity in Triceps Lateral Head at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F3**

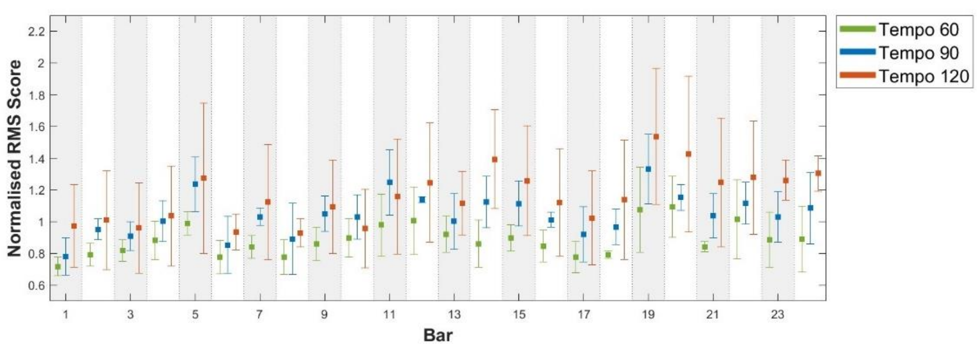
*Bar-to-Bar Muscle Activity in Biceps at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F4**

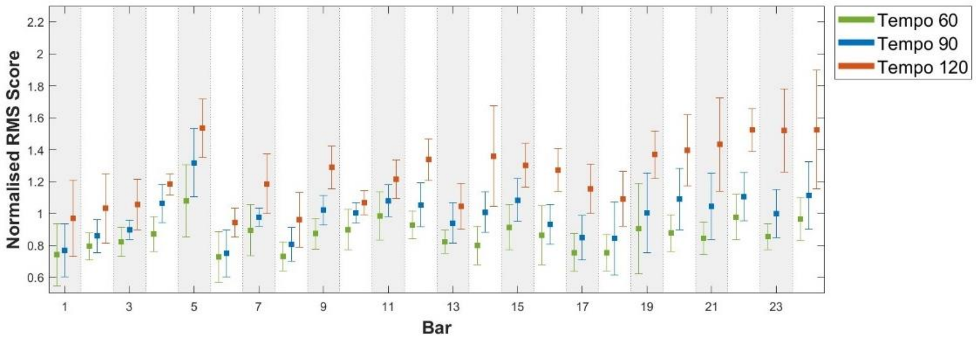
*Bar-to-Bar Muscle Activity in Flexor Digitorum Superficialis at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F5**

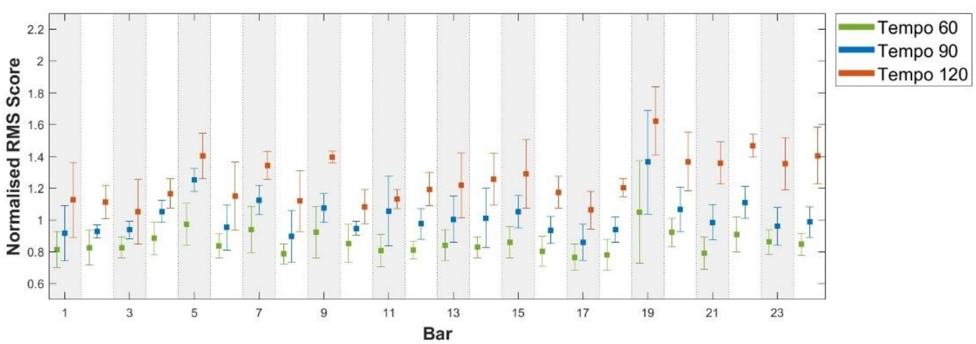
*Bar-to-Bar Muscle Activity in Flexor Carpi Radialis at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F6**

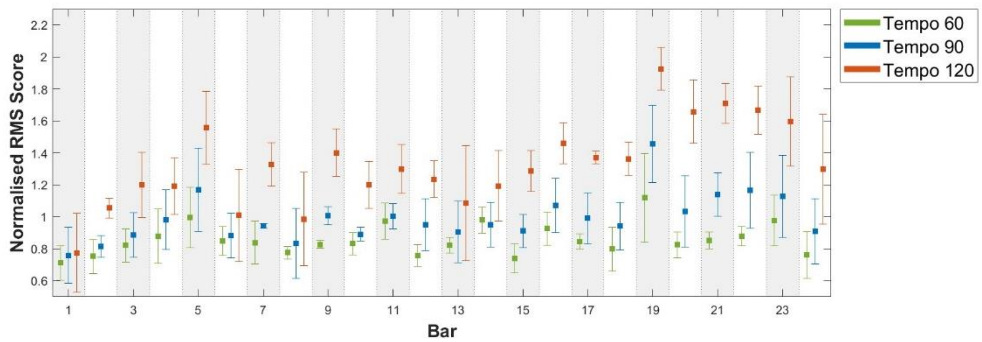
*Bar-to-Bar Muscle Activity in Flexor Pollicis Longus at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F7**

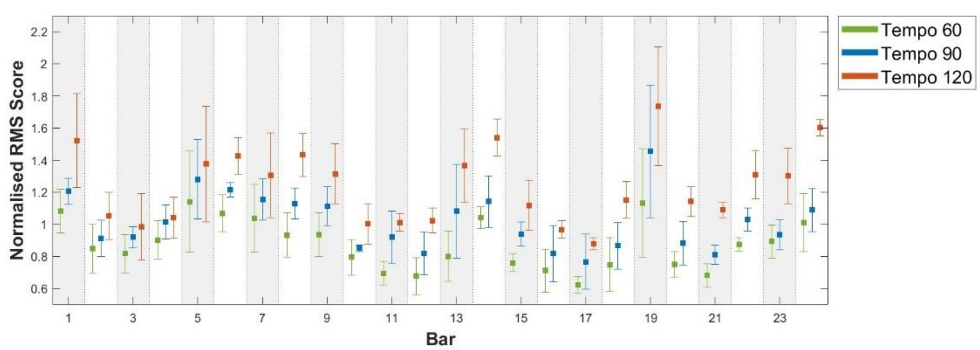
*Bar-to-Bar Muscle Activity in Extensor Digitorum at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

**Figure F8**

*Bar-to-Bar Muscle Activity in Extensor Pollicis Longus at Three Different Playing Speeds*




*Note.* The grey and white bars in the background are visual aids to separate the values from each bar. Each dot represents an average normalised RMS score (muscle activity) from the seven trails of all participants. The error bars are derived from the standard deviations, indicating the variabilities around the means from all participants.

# Appendix G

## Bar-to-Bar Mean Normalised RMS Scores in Each Muscle

**Table G1**

*The Mean Normalised RMS Scores from the Latissimus Dorsi*

| Tempo | | Bar 1 | Bar 2 | Bar 3 | Bar 4 | Bar 5 | Bar 6 | Bar 7 | Bar 8 | Bar 9 | Bar 10 | Bar 11 | Bar 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 1.27 | 0.81 | 0.84 | 0.87 | 0.94 | 0.81 | 0.87 | 0.79 | 0.77 | 0.83 | 0.88 | 0.82 |
| | *SD* | 0.69 | 0.15 | 0.04 | 0.10 | 0.20 | 0.13 | 0.18 | 0.13 | 0.12 | 0.14 | 0.17 | 0.15 |
| Medium | *M* | 0.83 | 0.78 | 0.78 | 0.89 | 0.90 | 0.82 | 0.84 | 0.82 | 0.83 | 0.84 | 0.87 | 0.84 |
| | *SD* | 0.13 | 0.11 | 0.14 | 0.17 | 0.19 | 0.14 | 0.14 | 0.15 | 0.17 | 0.17 | 0.18 | 0.11 |
| Fast | *M* | 0.91 | 0.91 | 0.88 | 1.01 | 1.16 | 0.95 | 1.09 | 1.00 | 1.01 | 1.03 | 1.11 | 1.01 |
| | *SD* | 0.18 | 0.17 | 0.18 | 0.18 | 0.32 | 0.18 | 0.25 | 0.26 | 0.24 | 0.22 | 0.30 | 0.22 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.87 | 0.94 | 0.84 | 0.78 | 0.76 | 0.79 | 0.88 | 0.90 | 0.79 | 0.81 | 0.76 | 0.80 |
| | *SD* | 0.15 | 0.20 | 0.19 | 0.13 | 0.11 | 0.12 | 0.18 | 0.21 | 0.14 | 0.12 | 0.13 | 0.16 |
| Medium | *M* | 0.95 | 1.00 | 0.89 | 0.80 | 0.74 | 0.83 | 0.87 | 0.95 | 0.86 | 0.86 | 0.79 | 0.84 |
| | *SD* | 0.14 | 0.20 | 0.17 | 0.13 | 0.10 | 0.15 | 0.13 | 0.19 | 0.14 | 0.17 | 0.13 | 0.15 |
| Fast | *M* | 1.28 | 1.48 | 1.20 | 1.02 | 0.94 | 1.10 | 1.15 | 1.35 | 1.09 | 1.11 | 1.04 | 1.13 |
| | *SD* | 0.31 | 0.40 | 0.24 | 0.27 | 0.25 | 0.32 | 0.35 | 0.26 | 0.26 | 0.26 | 0.19 | 0.25 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G2**

*The Mean Normalised RMS Scores from the Triceps Lateral Head*

| Tempo | | Bar 1 | Bar 2 | Bar 3 | Bar 4 | Bar 5 | Bar 6 | Bar 7 | Bar 8 | Bar 9 | Bar 10 | Bar 11 | Bar 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 0.82 | 0.88 | 0.92 | 1.02 | 1.19 | 0.94 | 0.98 | 0.84 | 1.04 | 0.94 | 1.05 | 0.96 |
| | *SD* | 0.16 | 0.23 | 0.18 | 0.20 | 0.22 | 0.26 | 0.25 | 0.11 | 0.18 | 0.20 | 0.13 | 0.16 |
| Medium | *M* | 0.92 | 0.99 | 1.00 | 1.12 | 1.46 | 0.97 | 1.12 | 0.86 | 1.01 | 0.97 | 1.21 | 1.18 |
| | *SD* | 0.36 | 0.36 | 0.20 | 0.18 | 0.31 | 0.21 | 0.19 | 0.09 | 0.20 | 0.14 | 0.31 | 0.17 |
| Fast | *M* | 0.84 | 0.94 | 0.90 | 1.06 | 1.30 | 0.91 | 1.18 | 0.81 | 1.08 | 0.81 | 0.97 | 1.05 |
| | *SD* | 0.17 | 0.27 | 0.19 | 0.24 | 0.21 | 0.10 | 0.30 | 0.09 | 0.21 | 0.20 | 0.13 | 0.10 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.94 | 0.83 | 0.91 | 0.79 | 0.75 | 0.78 | 0.84 | 1.01 | 0.94 | 1.10 | 1.00 | 0.94 |
| | *SD* | 0.13 | 0.19 | 0.12 | 0.19 | 0.13 | 0.24 | 0.29 | 0.13 | 0.19 | 0.11 | 0.19 | 0.05 |
| Medium | *M* | 1.13 | 1.23 | 1.17 | 0.79 | 0.73 | 0.78 | 1.07 | 1.31 | 1.11 | 1.11 | 1.13 | 1.22 |
| | *SD* | 0.18 | 0.32 | 0.39 | 0.16 | 0.08 | 0.13 | 0.32 | 0.33 | 0.18 | 0.22 | 0.23 | 0.29 |
| Fast | *M* | 1.06 | 1.39 | 1.25 | 0.95 | 0.80 | 0.90 | 1.11 | 1.42 | 1.26 | 1.22 | 1.28 | 1.47 |
| | *SD* | 0.23 | 0.37 | 0.14 | 0.11 | 0.06 | 0.15 | 0.09 | 0.28 | 0.30 | 0.23 | 0.33 | 0.40 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G3**

*The Mean Normalised RMS Scores from the Biceps*

| **Tempo** | | **Bar 1** | **Bar 2** | **Bar 3** | **Bar 4** | **Bar 5** | **Bar 6** | **Bar 7** | **Bar 8** | **Bar 9** | **Bar 10** | **Bar 11** | **Bar 12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 0.94 | 0.81 | 0.85 | 0.88 | 0.85 | 0.80 | 0.91 | 0.84 | 0.90 | 0.80 | 0.80 | 0.85 |
| | *SD* | 0.22 | 0.11 | 0.19 | 0.16 | 0.09 | 0.14 | 0.24 | 0.16 | 0.21 | 0.21 | 0.19 | 0.22 |
| Medium | *M* | 1.00 | 0.95 | 0.85 | 0.91 | 1.18 | 0.95 | 1.19 | 0.92 | 0.99 | 0.90 | 0.92 | 0.98 |
| | *SD* | 0.28 | 0.17 | 0.16 | 0.09 | 0.11 | 0.17 | 0.39 | 0.09 | 0.22 | 0.19 | 0.15 | 0.24 |
| Fast | *M* | 1.07 | 0.98 | 0.94 | 1.14 | 1.43 | 1.22 | 1.27 | 1.12 | 1.15 | 0.99 | 0.99 | 0.99 |
| | *SD* | 0.25 | 0.13 | 0.16 | 0.25 | 0.33 | 0.34 | 0.25 | 0.19 | 0.24 | 0.20 | 0.12 | 0.15 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.74 | 0.81 | 0.82 | 0.78 | 0.78 | 0.80 | 0.89 | 0.90 | 0.87 | 0.88 | 0.86 | 0.87 |
| | *SD* | 0.06 | 0.09 | 0.12 | 0.09 | 0.12 | 0.13 | 0.22 | 0.13 | 0.21 | 0.18 | 0.16 | 0.17 |
| Medium | *M* | 1.07 | 1.06 | 1.23 | 0.91 | 0.77 | 0.82 | 1.15 | 1.21 | 1.10 | 1.00 | 0.96 | 1.12 |
| | *SD* | 0.07 | 0.23 | 0.27 | 0.12 | 0.11 | 0.18 | 0.28 | 0.38 | 0.21 | 0.31 | 0.17 | 0.15 |
| Fast | *M* | 1.23 | 1.60 | 1.38 | 1.09 | 0.93 | 0.97 | 1.36 | 1.38 | 1.11 | 1.20 | 1.15 | 1.33 |
| | *SD* | 0.39 | 0.47 | 0.32 | 0.07 | 0.07 | 0.14 | 0.29 | 0.36 | 0.20 | 0.28 | 0.27 | 0.17 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G4**

*The Mean Normalised RMS Scores from the Flexor Digitorum Superficialis*

| Tempo | | Bar 1 | Bar 2 | Bar 3 | Bar 4 | Bar 5 | Bar 6 | Bar 7 | Bar 8 | Bar 9 | Bar 10 | Bar 11 | Bar 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 0.72 | 0.79 | 0.82 | 0.88 | 0.99 | 0.78 | 0.84 | 0.78 | 0.86 | 0.90 | 0.98 | 1.01 |
| | *SD* | 0.06 | 0.07 | 0.07 | 0.12 | 0.07 | 0.11 | 0.07 | 0.11 | 0.11 | 0.12 | 0.19 | 0.21 |
| Medium | *M* | 0.78 | 0.95 | 0.91 | 1.00 | 1.24 | 0.85 | 1.03 | 0.89 | 1.05 | 1.03 | 1.25 | 1.14 |
| | *SD* | 0.12 | 0.07 | 0.09 | 0.13 | 0.17 | 0.18 | 0.06 | 0.22 | 0.11 | 0.14 | 0.21 | 0.02 |
| Fast | *M* | 0.97 | 1.01 | 0.96 | 1.04 | 1.27 | 0.94 | 1.13 | 0.93 | 1.10 | 0.96 | 1.16 | 1.25 |
| | *SD* | 0.26 | 0.31 | 0.28 | 0.32 | 0.47 | 0.11 | 0.36 | 0.09 | 0.29 | 0.25 | 0.36 | 0.37 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.92 | 0.86 | 0.90 | 0.85 | 0.78 | 0.79 | 1.08 | 1.09 | 0.84 | 1.01 | 0.89 | 0.89 |
| | *SD* | 0.11 | 0.15 | 0.08 | 0.10 | 0.10 | 0.02 | 0.27 | 0.19 | 0.03 | 0.25 | 0.17 | 0.21 |
| Medium | *M* | 1.00 | 1.12 | 1.11 | 1.01 | 0.92 | 0.97 | 1.33 | 1.15 | 1.04 | 1.12 | 1.03 | 1.09 |
| | *SD* | 0.18 | 0.16 | 0.14 | 0.05 | 0.17 | 0.11 | 0.22 | 0.08 | 0.14 | 0.13 | 0.16 | 0.23 |
| Fast | *M* | 1.12 | 1.39 | 1.26 | 1.12 | 1.02 | 1.14 | 1.54 | 1.43 | 1.25 | 1.28 | 1.26 | 1.30 |
| | *SD* | 0.20 | 0.31 | 0.34 | 0.34 | 0.30 | 0.37 | 0.43 | 0.49 | 0.41 | 0.36 | 0.13 | 0.11 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G5**

*The Mean Normalised RMS Scores from the Flexor Carpi Radialis*

| **Tempo** | | **Bar 1** | **Bar 2** | **Bar 3** | **Bar 4** | **Bar 5** | **Bar 6** | **Bar 7** | **Bar 8** | **Bar 9** | **Bar 10** | **Bar 11** | **Bar 12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 0.74 | 0.79 | 0.82 | 0.87 | 1.08 | 0.73 | 0.90 | 0.73 | 0.87 | 0.90 | 0.99 | 0.93 |
| | *SD* | 0.19 | 0.08 | 0.09 | 0.11 | 0.22 | 0.16 | 0.16 | 0.09 | 0.10 | 0.13 | 0.15 | 0.09 |
| Medium | *M* | 0.77 | 0.86 | 0.90 | 1.06 | 1.32 | 0.75 | 0.98 | 0.81 | 1.02 | 1.00 | 1.08 | 1.05 |
| | *SD* | 0.17 | 0.10 | 0.06 | 0.12 | 0.21 | 0.15 | 0.06 | 0.11 | 0.09 | 0.06 | 0.10 | 0.14 |
| Fast | *M* | 0.97 | 1.03 | 1.06 | 1.18 | 1.54 | 0.94 | 1.19 | 0.96 | 1.29 | 1.07 | 1.22 | 1.34 |
| | *SD* | 0.24 | 0.22 | 0.16 | 0.07 | 0.18 | 0.09 | 0.19 | 0.17 | 0.13 | 0.08 | 0.12 | 0.13 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.82 | 0.80 | 0.91 | 0.87 | 0.76 | 0.75 | 0.91 | 0.88 | 0.84 | 0.98 | 0.86 | 0.97 |
| | *SD* | 0.07 | 0.12 | 0.14 | 0.18 | 0.12 | 0.11 | 0.28 | 0.12 | 0.10 | 0.14 | 0.08 | 0.13 |
| Medium | *M* | 0.94 | 1.01 | 1.08 | 0.93 | 0.85 | 0.84 | 1.00 | 1.09 | 1.05 | 1.11 | 1.00 | 1.11 |
| | *SD* | 0.13 | 0.13 | 0.13 | 0.13 | 0.14 | 0.23 | 0.25 | 0.19 | 0.21 | 0.15 | 0.15 | 0.21 |
| Fast | *M* | 1.05 | 1.36 | 1.30 | 1.27 | 1.16 | 1.09 | 1.37 | 1.40 | 1.43 | 1.52 | 1.52 | 1.53 |
| | *SD* | 0.14 | 0.31 | 0.14 | 0.13 | 0.15 | 0.17 | 0.15 | 0.22 | 0.29 | 0.14 | 0.26 | 0.37 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G6**

*The Mean Normalised RMS Scores from the Flexor Pollicis Longus*

| **Tempo** | | **Bar 1** | **Bar 2** | **Bar 3** | **Bar 4** | **Bar 5** | **Bar 6** | **Bar 7** | **Bar 8** | **Bar 9** | **Bar 10** | **Bar 11** | **Bar 12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 0.82 | 0.83 | 0.83 | 0.89 | 0.97 | 0.84 | 0.94 | 0.79 | 0.93 | 0.85 | 0.81 | 0.81 |
| | *SD* | 0.11 | 0.11 | 0.07 | 0.10 | 0.13 | 0.08 | 0.15 | 0.06 | 0.16 | 0.12 | 0.10 | 0.06 |
| Medium | *M* | 0.92 | 0.93 | 0.94 | 1.05 | 1.25 | 0.95 | 1.13 | 0.90 | 1.07 | 0.95 | 1.06 | 0.98 |
| | *SD* | 0.17 | 0.04 | 0.05 | 0.07 | 0.07 | 0.14 | 0.09 | 0.16 | 0.09 | 0.04 | 0.22 | 0.10 |
| Fast | *M* | 1.13 | 1.11 | 1.05 | 1.17 | 1.40 | 1.15 | 1.34 | 1.12 | 1.40 | 1.08 | 1.13 | 1.19 |
| | *SD* | 0.24 | 0.10 | 0.20 | 0.09 | 0.14 | 0.21 | 0.09 | 0.19 | 0.04 | 0.11 | 0.06 | 0.10 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.84 | 0.83 | 0.86 | 0.80 | 0.77 | 0.78 | 1.05 | 0.92 | 0.79 | 0.91 | 0.86 | 0.85 |
| | *SD* | 0.10 | 0.07 | 0.10 | 0.09 | 0.08 | 0.10 | 0.32 | 0.09 | 0.10 | 0.11 | 0.08 | 0.07 |
| Medium | *M* | 1.01 | 1.01 | 1.05 | 0.94 | 0.86 | 0.94 | 1.37 | 1.07 | 0.99 | 1.11 | 0.96 | 0.99 |
| | *SD* | 0.15 | 0.19 | 0.10 | 0.08 | 0.11 | 0.08 | 0.33 | 0.14 | 0.11 | 0.10 | 0.12 | 0.10 |
| Fast | *M* | 1.22 | 1.26 | 1.29 | 1.17 | 1.06 | 1.20 | 1.62 | 1.37 | 1.36 | 1.47 | 1.35 | 1.41 |
| | *SD* | 0.20 | 0.16 | 0.21 | 0.10 | 0.12 | 0.06 | 0.21 | 0.18 | 0.13 | 0.07 | 0.17 | 0.18 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G7**

*The Mean Normalised RMS Scores from the Extensor Digitorum*

| **Tempo** | | **Bar 1** | **Bar 2** | **Bar 3** | **Bar 4** | **Bar 5** | **Bar 6** | **Bar 7** | **Bar 8** | **Bar 9** | **Bar 10** | **Bar 11** | **Bar 12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 0.71 | 0.75 | 0.82 | 0.88 | 1.00 | 0.85 | 0.84 | 0.78 | 0.83 | 0.83 | 0.97 | 0.76 |
| | *SD* | 0.11 | 0.11 | 0.10 | 0.17 | 0.19 | 0.09 | 0.13 | 0.04 | 0.02 | 0.07 | 0.11 | 0.07 |
| Medium | *M* | 0.76 | 0.82 | 0.89 | 0.98 | 1.17 | 0.88 | 0.94 | 0.83 | 1.01 | 0.89 | 1.00 | 0.95 |
| | *SD* | 0.17 | 0.07 | 0.14 | 0.19 | 0.26 | 0.14 | 0.02 | 0.22 | 0.06 | 0.04 | 0.08 | 0.16 |
| Fast | *M* | 0.78 | 1.06 | 1.20 | 1.19 | 1.56 | 1.01 | 1.33 | 0.99 | 1.40 | 1.20 | 1.30 | 1.23 |
| | *SD* | 0.25 | 0.06 | 0.20 | 0.18 | 0.23 | 0.29 | 0.14 | 0.29 | 0.15 | 0.15 | 0.15 | 0.12 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.82 | 0.98 | 0.74 | 0.93 | 0.85 | 0.80 | 1.12 | 0.82 | 0.85 | 0.88 | 0.98 | 0.76 |
| | *SD* | 0.05 | 0.08 | 0.09 | 0.10 | 0.05 | 0.14 | 0.28 | 0.08 | 0.05 | 0.06 | 0.16 | 0.15 |
| Medium | *M* | 0.90 | 0.95 | 0.91 | 1.07 | 0.99 | 0.94 | 1.46 | 1.03 | 1.14 | 1.17 | 1.13 | 0.91 |
| | *SD* | 0.19 | 0.14 | 0.10 | 0.17 | 0.16 | 0.15 | 0.24 | 0.22 | 0.14 | 0.24 | 0.26 | 0.20 |
| Fast | *M* | 1.09 | 1.19 | 1.29 | 1.46 | 1.37 | 1.36 | 1.93 | 1.66 | 1.71 | 1.67 | 1.60 | 1.30 |
| | *SD* | 0.36 | 0.22 | 0.13 | 0.13 | 0.04 | 0.10 | 0.13 | 0.20 | 0.12 | 0.15 | 0.28 | 0.34 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

**Table G8**

*The Mean Normalised RMS Scores from the Extensor Pollicis Longus*

| **Tempo** | | **Bar 1** | **Bar 2** | **Bar 3** | **Bar 4** | **Bar 5** | **Bar 6** | **Bar 7** | **Bar 8** | **Bar 9** | **Bar 10** | **Bar 11** | **Bar 12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 1.08 | 0.85 | 0.82 | 0.90 | 1.14 | 1.07 | 1.04 | 0.93 | 0.94 | 0.79 | 0.70 | 0.68 |
| | *SD* | 0.13 | 0.15 | 0.12 | 0.12 | 0.31 | 0.12 | 0.21 | 0.14 | 0.13 | 0.11 | 0.07 | 0.11 |
| Medium | *M* | 1.21 | 0.91 | 0.92 | 1.01 | 1.28 | 1.22 | 1.16 | 1.13 | 1.11 | 0.85 | 0.92 | 0.82 |
| | *SD* | 0.08 | 0.11 | 0.07 | 0.11 | 0.25 | 0.04 | 0.13 | 0.10 | 0.12 | 0.02 | 0.16 | 0.13 |
| Fast | *M* | 1.52 | 1.05 | 0.98 | 1.04 | 1.38 | 1.43 | 1.31 | 1.43 | 1.31 | 1.00 | 1.01 | 1.02 |
| | *SD* | 0.29 | 0.15 | 0.21 | 0.13 | 0.36 | 0.11 | 0.26 | 0.13 | 0.19 | 0.13 | 0.06 | 0.08 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 0.80 | 1.04 | 0.76 | 0.71 | 0.62 | 0.75 | 1.13 | 0.75 | 0.68 | 0.88 | 0.89 | 1.01 |
| | *SD* | 0.16 | 0.07 | 0.05 | 0.13 | 0.05 | 0.17 | 0.34 | 0.08 | 0.07 | 0.04 | 0.10 | 0.18 |
| Medium | *M* | 1.08 | 1.14 | 0.94 | 0.82 | 0.77 | 0.87 | 1.46 | 0.88 | 0.81 | 1.03 | 0.94 | 1.09 |
| | *SD* | 0.29 | 0.16 | 0.08 | 0.18 | 0.17 | 0.15 | 0.41 | 0.14 | 0.06 | 0.07 | 0.09 | 0.13 |
| Fast | *M* | 1.37 | 1.54 | 1.12 | 0.97 | 0.88 | 1.15 | 1.74 | 1.14 | 1.09 | 1.31 | 1.30 | 1.60 |
| | *SD* | 0.23 | 0.11 | 0.15 | 0.05 | 0.04 | 0.11 | 0.37 | 0.09 | 0.05 | 0.15 | 0.17 | 0.05 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The means were calculated from the normalised RMS scores from the seven trials from all participants. The standard deviations indicate the variabilities around the means of all participants.

# Appendix H

## Key Pressing Velocities from the Left and the Right Hand

**Table H1**

*The Key Pressing Velocity from the Left Hand*

| **Tempo** | | **Bar 1** | **Bar 2** | **Bar 3** | **Bar 4** | **Bar 5** | **Bar 6** | **Bar 7** | **Bar 8** | **Bar 9** | **Bar 10** | **Bar 11** | **Bar 12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 63.34 | 57.91 | 56.89 | 64.53 | 64.95 | 65.70 | 63.05 | 65.08 | 62.07 | 64.63 | 65.62 | 62.35 |
| | *SD* | 2.85 | 4.58 | 4.17 | 4.53 | 4.77 | 5.50 | 3.18 | 5.57 | 3.31 | 5.48 | 6.58 | 7.30 |
| Medium | *M* | 59.06 | 56.75 | 55.94 | 60.72 | 59.47 | 61.71 | 60.07 | 60.08 | 59.86 | 56.75 | 61.83 | 56.34 |
| | *SD* | 3.11 | 4.09 | 4.82 | 1.92 | 4.96 | 2.73 | 2.48 | 1.21 | 2.82 | 1.30 | 5.52 | 5.90 |
| Fast | *M* | 59.66 | 56.34 | 54.50 | 60.59 | 62.22 | 62.79 | 60.57 | 61.60 | 58.96 | 57.32 | 63.28 | 56.23 |
| | *SD* | 4.09 | 7.08 | 6.62 | 3.42 | 2.69 | 2.16 | 3.90 | 1.15 | 5.22 | 3.79 | 2.77 | 4.54 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 61.72 | 61.95 | 63.40 | 61.37 | 64.40 | 63.45 | 65.26 | 65.61 | 66.84 | 63.59 | 64.62 | 66.30 |
| | *SD* | 8.38 | 7.52 | 5.56 | 7.63 | 7.35 | 6.62 | 8.37 | 9.03 | 6.52 | 8.63 | 6.50 | 5.09 |
| Medium | *M* | 53.62 | 58.21 | 63.02 | 55.31 | 57.74 | 61.89 | 60.52 | 63.20 | 64.32 | 60.90 | 62.33 | 63.44 |
| | *SD* | 6.94 | 4.31 | 3.55 | 5.57 | 5.94 | 5.36 | 6.25 | 8.99 | 5.66 | 8.54 | 4.72 | 7.63 |
| Fast | *M* | 59.06 | 59.04 | 64.06 | 59.19 | 59.56 | 59.08 | 62.44 | 62.34 | 62.63 | 59.62 | 61.89 | 61.93 |
| | *SD* | 5.40 | 7.10 | 4.03 | 4.25 | 6.32 | 2.57 | 5.65 | 9.31 | 4.14 | 6.45 | 2.50 | 3.45 |

*Note.* The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The key pressing velocity is specified as an integer ranged between 0 and 127 in the MIDI messages and describes how fast or hard a note is played.

**Table H2**

*The Key Pressing Velocity from the Right Hand*

| Tempo | | Bar 1 | Bar 2 | Bar 3 | Bar 4 | Bar 5 | Bar 6 | Bar 7 | Bar 8 | Bar 9 | Bar 10 | Bar 11 | Bar 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slow | *M* | 78.42 | 84.76 | 83.09 | 83.19 | 81.38 | 78.78 | 82.57 | 79.40 | 85.58 | 80.10 | 81.10 | 79.91 |
| | *SD* | 5.07 | 5.05 | 6.22 | 6.23 | 5.72 | 7.28 | 5.68 | 7.63 | 5.70 | 6.79 | 7.18 | 8.87 |
| Medium | *M* | 73.70 | 78.83 | 77.93 | 78.99 | 76.95 | 75.06 | 78.25 | 73.92 | 81.32 | 74.02 | 74.18 | 72.85 |
| | *SD* | 3.10 | 3.88 | 3.49 | 3.84 | 4.34 | 3.39 | 4.88 | 5.55 | 4.33 | 4.23 | 3.02 | 6.51 |
| Fast | *M* | 69.11 | 77.82 | 78.16 | 77.43 | 74.01 | 72.52 | 77.69 | 73.67 | 80.78 | 74.65 | 75.82 | 75.19 |
| | *SD* | 2.49 | 2.31 | 1.82 | 2.70 | 1.64 | 1.76 | 3.70 | 2.78 | 1.64 | 2.13 | 1.25 | 3.81 |
| **Tempo** | | **Bar 13** | **Bar 14** | **Bar 15** | **Bar 16** | **Bar 17** | **Bar 18** | **Bar 19** | **Bar 20** | **Bar 21** | **Bar 22** | **Bar 23** | **Bar 24** |
| Slow | *M* | 76.21 | 73.83 | 76.06 | 79.83 | 79.77 | 76.61 | 80.02 | 77.13 | 78.96 | 80.08 | 82.47 | 82.56 |
| | *SD* | 7.75 | 7.36 | 6.87 | 9.48 | 9.16 | 9.23 | 9.02 | 5.92 | 5.75 | 5.48 | 3.65 | 4.12 |
| Medium | *M* | 67.99 | 70.42 | 67.92 | 72.71 | 72.41 | 67.63 | 75.51 | 66.16 | 68.81 | 71.71 | 75.62 | 75.35 |
| | *SD* | 4.88 | 5.30 | 3.18 | 6.58 | 7.40 | 7.29 | 7.26 | 6.24 | 7.03 | 5.71 | 5.37 | 6.52 |
| Fast | *M* | 69.44 | 68.57 | 70.22 | 74.99 | 73.90 | 70.19 | 74.26 | 69.05 | 72.53 | 74.74 | 77.26 | 77.14 |
| | *SD* | 3.71 | 2.23 | 3.03 | 2.14 | 4.27 | 2.90 | 2.04 | 3.16 | 5.25 | 4.91 | 5.31 | 5.31 |

*Note*. The slow, medium, and fast tempi are 60, 90, 120 bpm, respectively. The key pressing velocity is specified as an integer ranged between 0 and 127 in the MIDI messages and describes how fast or hard a note is played.