3D BIOMECHANICAL QUANTIFICATION OF PIANO MOTOR SKILLS

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DEDICATION

To my Mom, Dad, and brother, Eric, for their love and support.

ABSTRACT

To date, systematic biomechanical explorations of music performance have been scarce. In many human activities, movement science methodologies have helped accelerate the learning process, prevent injuries, improve teaching practices, and optimize performance outcomes. The current thesis postulates that a consideration of individualization with respect to biomechanics, anthropometry, and musical strategization can provide musicians with an approach to motor learning where outcomes may be optimized while simultaneously reducing risk of playing-related injury. The thesis is comprised of three case comparison studies using 3D motion capture, biomechanical modeling, and force plate measurements to quantify pianists' motor behaviours in a variety of performance contexts. The framework established in the thesis is interdisciplinary and provides a model that aims to be "artful" in its efforts to ensure that its analyses of motor behaviours are sensitive to musical intentionality and, thus, can be relevant to musicians.

PREFACE

The contents of Chapters 2 and 3 of this thesis have been published as follows:

(1) Turner, C., Visentin, P., & Shan, G. (2021). Wrist internal loading and tempo-dependent, effort-reducing motor behaviour strategies for two elite pianists. *Medical Problems of Performing Artists, 36*(3), 141-149. https://doi.org/10.21091/mppa.2021.3017.

(2) Turner, C., Visentin, P., Oye, D., Rathwell, S., & Shan, G. (2021). Pursuing artful movement science in music performance: Single subject motor analysis with two elite pianists. *Perceptual and Motor Skills, 128*(3), 1252-1274. https://doi.org/10.1177/00315125211003493

CONTRIBUTIONS OF AUTHORS

All chapters in this thesis are based on research by Craig Turner, Gongbing Shan, and Peter Visentin that was conducted at the University of Lethbridge's Biomechanics laboratory. I, Craig Turner, was the main contributor for all efforts involved with the research and writing of all material presented in this thesis.

For article #1, I performed the literature review, designed the research protocol, recruited participants, collected data, processed, analyzed and interpreted the data, and wrote the manuscript. Peter Visentin and Gongbing Shan contributed to the research protocol, collection of data, analysis and interpretation of the data, and the writing of the manuscript. Permission to include the article in this thesis was obtained from the *Medical Problems of Performing Artists* journal.

For article #2, the contributions of Peter Visentin, Gongbing Shan, and I were the same as article #1. Deanna Oye provided feedback on the research protocol and was involved in discussions related to data interpretation. Scott Rathwell contributed suggestions during the editing process of the manuscript. This article was published open access in the *Perceptual and Motor Skills* journal.

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I would also like to sincerely thank Peter Visentin for the many discussions which led to deep and innovative research connections between art and science. I genuinely looked forward to our writing sessions, as each one greatly improved my critical thinking and writing abilities. I appreciate all of our conversations.

My continued growth as a pianist would not be possible without Deanna Oye. Lessons with her not only shaped my philosophical approach to and appreciation of music, but also gave me the opportunity to connect my research to the practical application of piano performance. Thank you, Deanna.

I feel extremely fortunate to have Bing, Peter, and Deanna as mentors during my time at the University of Lethbridge and they have significantly added to the value of my degrees.

Thank you to both Alan Watson and Scott Rathwell for their time and input as members of my thesis committee.

Finally, I would also like to thank Austin Culler, Ron Garnett, and Tom Gorges for moving the motion capture system down to the recital hall and assisting in data collection.

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LIST OF ABBREVIATIONS

3D	Three-Dimensional
A	Participant A (chapter 3)
Abb/Add	Abduction/Adduction
Ant/Post	Anterior/Posterior
B	Participant B (chapter 3)
Bpm	Beats Per Minute
COG	Center of Gravity
CV	Critical Value
FFT	Fast Fourier Transform
FL	Fundamental Loading
Flex/ext	Flexion/Extension
IML	Impact Loading
LH	Left Hand
Med/Lat	Medial/Lateral
N/s	Notes per Second
P1	Part 1 (chapter 3); Participant/Pianist 1 (chapter 4)
P2	Part 2 (chapter 3); Participant/Pianist 2 (chapter 4)
P3	Part 3 (chapter 3); Participant/Pianist 3 (chapter 4)
PRMP	Playing Related Musculoskeletal Problems
PRMD	Playing Related Musculoskeletal Disorders
Rad/uln	Radial/Ulnar Deviation
RH	Right Hand
ROM	Range of Motion
WIL	Wrist Internal Loading

CHAPTER 1: THESIS INTRODUCTION

The analytic tools of biomechanics have changed the way humans interact with their world. With 20th- and 21st-century advancements in technology, biomechanics has contributed to improvements in sports, ergonomics, equipment design, quality of life, and many other fields (Li, 2012; Lu & Chang, 2012; Stefanyshyn & Wannop, 2015). To date, however, scientific exploration of biomechanics in the field of music performance has been sparse. For a discipline that is so clearly dependent on the development of finely honed motor behaviours, the paucity of biomechanics research, particularly in instrumental music performance, is puzzling. The results of the current thesis provide insight into why this might be the case and, through its three separate studies, provides a framework to answer the question, “What can we do about it?”.

To achieve their desired musical outcomes, instrumental musicians must engage in both feedback and feed-forward cognitive processes, all the while coordinating intricate fine and gross motor skills in the service of musical intentionality. This requires years of training.

> The world’s foremost cellist, Pablo Casals, (was) 83 (when he) was asked… why he continued to practice four and five hours a day. Casals answered, **“Because I think I am making progress.”** (Anonymous, 1959, p. 30)

When it comes to motor learning, the methods of modern biomechanics have great potential to accelerate the learning process while helping solve injury problems, improve teaching practices, and optimize performance outcomes (Visentin et al., 2008). Unfortunately, the majority of western pedagogical practices rely upon centuries-old, tradition-based, master-pupil teaching strategies that are, for the most part, only nominally systematic (Purser, 2005; Norton et al., 2015; Visentin et al., 2015). In such a culture, performers obsessively spend long hours engaging in “trial-and-error” practicing and the high rates of vocational injuries observed among musicians should not be surprising. Rates of playing-related musculoskeletal problem can be as high as 87% (Pratt et al., 1992; Silva et al., 2015). Many injuries can be career-ending for professional musicians. Given its successful application in other disciplines, such as sports (Glazier & Mehdizadeh, 2019; Zhang et al., 2019), it is reasonable to postulate that biomechanics research has the potential to improve music pedagogy, make music learning more efficient and effective, and help reduce epidemic rates of musicians’ injuries.

The reason that biomechanics of music performance research is sparse to date may be attributable to cultural norms in both the disciplines of music and biomechanics. Music performance culture holds its traditions very dear. In music, pedagogical practices strongly rely on teachers’ personal perceptions of their own experiences (Odena & Welch, 2012; Visentin et al., 2015). This pedagogical approach could foster artistry in a manner that favours creative individualization over mere reproduction of iconic performance exemplars. In terms of the culture of biomechanics research, scientific methods and analytic techniques typically seek to ensure repeatability of measures. Given that artistry is necessarily highly individualized, this makes meaningful application of biomechanics methodologies to music performance very challenging.

To solve problems related to playing-related injuries, improve efficiency of teaching practices, and optimize performance outcomes, application of biomechanics methodologies has great potential, but only if used in a manner that musicians perceive as being sensitive to the artistic ideal. To date, some research domains have studied music performance dating back to the 1980s with the emergence of performing arts medicine. If music performance is the central object of study, music motor behaviour research must become more "artful" in its analytic motivation and methods so that research design informs artistry rather than merely describing performance gestures. From a practical standpoint, analyses of motor behaviours will be most meaningful if they are sensitive to both a performer's musical intentionality and his/her potential for motor strategization, developed over decades of practice.

The current thesis is comprised of three independent research studies, each using methodologies from the field of biomechanics to quantify pianists' motor behaviours in a variety of different performance contexts. These studies employ 3D motion capture, biomechanical modeling, and force plate measurements in a series of case comparisons. Each study employs a different biomechanical approach, collectively providing a conceptual framework that lends utility to studies of biomechanics in the context of music performance. Study #1 focuses on mechanisms of injury by analyzing the kinetics of wrist movement in two expert pianists. It documents observed motor behaviour differences in terms of ergonomics, anthropometry, and effort-reducing performance strategization. Study #2 examines upper body kinematics and center of gravity shifts for two anthropometrically different pianists. The study aims to address how each pianists' gross motor behaviours can be influenced in terms of anthropometry and musical context. Study #3 discusses movement-based preparation strategies and trunk/right-hand coordination while considering anthropometry, skill level of the performer, and musical context. The first two of these studies have been accepted for publication in 2021. The third is currently under consideration. Since each of these was written with a specific journal in mind, introductions, literature reviews, data analysis, discussions, and conclusions are embedded in the articles rather than summarized in independent thesis chapters.

The thesis provides a series of interdisciplinary research frameworks that have ramifications for future biomechanical studies of music performance. A better understanding of biomechanics can aid teachers and artists in their efforts to optimize motor skill strategization. Improved motor strategization can consequently improve piano teaching and learning, so that skills are acquired more quickly while long hours of practice can be made more effective. Ultimately, the goal of every performer is to improve and deepen the concert-going experience for the listener. The practical goal of the current thesis was to provide research exemplars that will be meaningful to both researchers and performers.

CHAPTER 2: WRIST INTERNAL LOADING AND TEMPO-DEPENDENT, EFFORT-REDUCING MOTOR BEHAVIOUR STRATEGIES FOR TWO ELITE PIANISTS

Note – the contents of this study are published in:

Turner, C., Visentin, P., & Shan, G. (2021b). Wrist internal loading and tempo-dependent, effort-reducing motor behaviour strategies for two elite pianists. *Medical Problems of Performing Artists, 36*(3), 141-149. https://doi.org/10.21091/mppa.2021.3017

2.1 INTRODUCTION

Since performing music involves highly complex and repetitive low-load motor behaviours which must be precisely executed, all musicians can benefit from research dedicated to improving mechanical efficiencies during performance (Shan et al., 2004). Playing-related musculoskeletal problems (PRMP), disorders (PRMD), and pain prevalence among adult and/or professional musicians is common, with rates as high as 60% to 87% (Allsop & Ackland, 2010; Kaufman-Cohen et al., 2018; Larsson et al., 1993; Pratt et al., 1992; Silva et al., 2015; Zaza, 1998). For pianists, rates are documented from 60.6% to 77% (Amaral Corrêa et al., 2018; Furuya et al., 2006; Wood, 2014) and they most frequently occur in the neck, back, shoulders, elbow/forearm, wrists, and hands (Amaral Corrêa et al., 2018; Bruno et al., 2008; Kaufman-Cohen et al., 2018). Problems include neurological disturbances (such as carpal tunnel syndrome), enthesopathy, tendinitis, tenosynovitis, and more (Sakai, 2002). Wrist PRMP are common, with 24%-36.6% of pianists affected (Bragge et al., 2008; Bruno et al., 2008; Furuya et al., 2006; Pak & Chesky, 2001; Shields & Dockrell, 2000).

In piano performance any injuries or pain will affect force production and inhibit motor behaviours, lowering performance quality. In a perfection-driven vocation, consequences of this can be dire.

> The wear and tear of playing an instrument are unseen by the audience, yet the consequences are all too familiar to many professional musicians…For a soloist or a freelancer, there is no equivalent of baseball's disabled list – no performance, no income (Lin, 2010).

Identified injury risk factors for piano performance include: insufficient warm-up and cool-down time, sudden increases in playing time, playing for more than 60 minutes without a break, practicing for more than 20 hours per week, playing technique, adverse working conditions, lack of exercise, hand size and genetics (Amaral Corrêa et al., 2018; Wristen, 2000; Yoshimura et al., 2006). Additionally, female musicians have been shown to experience higher complaint rates than males (Amaral Corrêa et al., 2018; De Smet et al., 1998; Furuya et al., 2006; Pak & Chesky, 2001; Revak, 1989) although this finding could be an artefact of workplace culture and reporting (Amaral Corrêa et al., 2018; Fry et al., 1988).

The current paper postulates that, since playing the piano requires both gross and fine motor behaviours using an instrument that has fixed dimensions and is immobile during performance, pianists' occupational injuries should be recognized, in part, as an ergonomic problem (Meinke, 1995). As loading and the cumulative effects of long-term activity involve internal biologic processes, the current paper extends application of motion capture and biomechanical modelling to the case of music performance. These technologies have proven to be an effective indirect method of measuring the effects of activity in sports (Pueo & Jimenez-Olmedo, 2017) and have shown utility in doing so for music performance (Albrecht et al., 2014; Ferrario et al., 2007; Visentin & Shan, 2004). The current research contributes to existing knowledge by providing kinetic analysis of wrist movement for a standardized piano performance task; the wrists are the location of the highest injury rates in the upper limbs Bruno et al., 2008). Analyzing load intensity, frequency and duration is a generally accepted means of identifying physical workload associated with occupational tasks (Fry, 1987; Visentin & Shan, 2004). The objectives of this study were to quantify internal loading in the wrists of two expert pianists and discuss observed differences in motor behaviours in terms of ergonomics, anthropometry, and effort-reducing performance strategies.

2.2 METHODS

2.2.1 DATA COLLECTION

Drawing on the upper-body biomechanical model established by Shan and Visentin, (Shan & Visentin, 2010; Visentin & Shan, 2003; Visentin et al., 2008; Visentin et al., 2015) the current study utilized a ten-camera VICON MX40 motion capture system to record and synchronize kinematics for two expert pianists. Data was collected at 200Hz frequency with sub-millimetre accuracy (<0.6 mm calibration error). Fourteen 3M™ Super-Reflective Tape markers essential for the upper body biomechanical model were placed on the following anatomical landmarks: the sternal end of the clavicle, xiphoid process of the sternum, C7, T10, and the right and left acromion, lateral epicondyle, radial styloid process and ulnar styloid process. Reference markers were placed as follows: two on the front of the head, two on the back of the head, one on the right scapula, and one on each of the left and right humerus and forearm. Additionally, eighty-eight markers were placed on the white and black piano keys to identify keystroke accuracy. From the kinematic data, computer reconstruction permitted modeling of the skeletal structure and its movement. Inertial characteristics of the body were estimated using anthropometric norms embedded in VICON's motion analysis software and following the standard practices in the field of biomechanics (Shan & Bohn, 2003; Winter, 1990). The biomechanical model quantified a value for wrist loading by using inverse dynamic analysis.

2.2.2 PARTICIPANTS

Two expert pianists, one male and one female, were recruited for the study. Both participants were right-handed, had doctoral degrees in piano performance, and were employed full-time as piano teachers and concert performers. The research protocol and informed consent processes were approved by the Human Subject Research Committee at the University of Lethbridge [approval #2018-098].

2.2.3 EXPERIMENTAL PROTOCOL

The protocol consisted of a modified B major scale played at a moderate volume and at different speeds. B major is a fundamental scale in piano playing because the black and white key combinations are complementary with a typical hand shape (length of the fingers). The scale was performed hands together in overlapping two-octave gestures, both ascending and descending (Figure 1). Participants performed the protocol from memory and did not use the piano pedals.

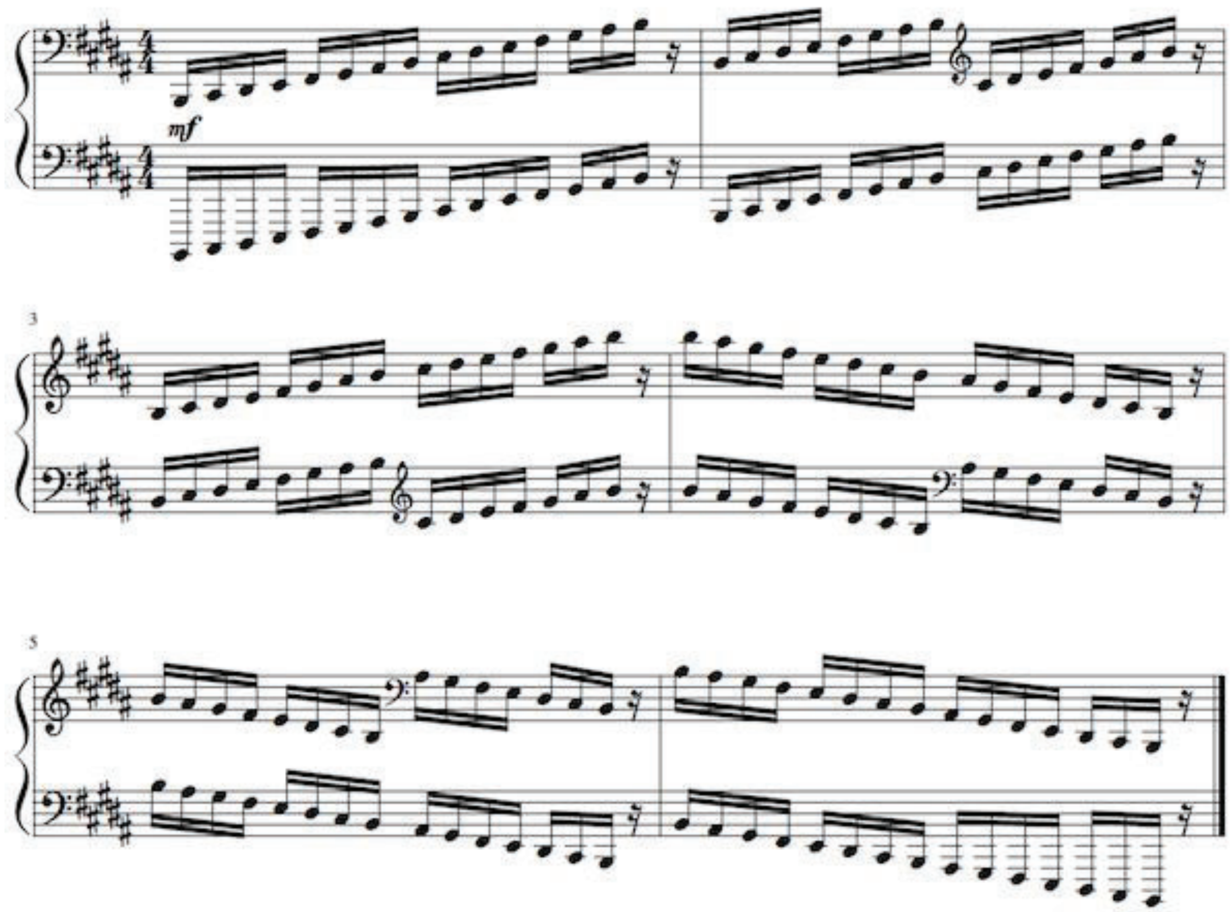


Figure 1: The B Major scale performed by the participants.

Five tempi were used: 4, 6, 8, 9, and 10 notes per second (N/s), representing a wide range of playing speeds with greater coverage at the fastest tempi where playing demands begin to become extreme. Data was collected in a concert hall where participants used a 9-foot New York Steinway concert grand piano. Participants adjusted bench height and seating distance from the keyboard according to personal preference and were permitted to warm-up for as long as they needed to feel comfortable with the instrument and the experimental environment. Anthropometric measurements necessary for biomechanical modeling and active range of motion (ROM) of the wrists was documented. For hand size, width was measured from the tip of the thumb to the 5th distal metacarpal while hand length was defined from the wrist to the 3rd distal metacarpal. Wrist ROM was quantified by asking the participants to move both wrists as far as possible in all planes of motion. Using motion capture and modeling, the wrist ROM values were determined. Finally, using the Beighton hypermobility protocol, it was determined that neither participant exhibited hypermobility in the upper limbs, including the wrists and fingers.

2.2.4 DATA PROCESSING AND ANALYSIS

Data were processed and analyzed using VICON Nexus software and Microsoft Excel 2017. The biomechanical model was based on a rigid-body system with multiple segments: head, trunk, shoulders, upper arms, forearms, and hands. Using inverse dynamic analysis, joint moments for the wrist were calculated from both kinematic data and the anthropometric properties of participants' hands. It should be noted that, in using this model the calculated wrist moment is a net moment generated by muscles around the wrist, i.e., net muscle loading. Thus, in the current study, wrist internal loading (WIL) data are idealized, where no inefficiencies from extraneous co-contraction of agonist and antagonist muscle groups are considered. This should be considered a minimum loading calculation when analysing injury risk. Actual muscle loading could be significantly higher depending on a pianist's efficiency of coordination. Well-trained pianists should have more optimized coordination amongst agonist and antagonist muscle groups than novices.

For low-load activities such as playing a musical instrument, fundamental loading (FL), the basic muscle workload used by an individual at his/her current level of motor skill development, may be very small. Quantification of cumulative load requires consideration of load character as well as duration of activity; both contribute to risk profile. Since, for a biologic system, load intensity is a variable that changes during the course of an activity, points where load intensity is greatest can be identified and examined for the possibility that motor efficiencies may be found (Visentin & Shan, 2004). In the current study, an activity-specific maximum for WIL was determined for each trial by averaging the three highest WIL data points. 70% of this calculated maximum WIL was used as a critical value (CV) threshold so that load variability during each trial could be examined. As seen in figure 2, the fundamental load (FL), shown in black, was determined using a Fast Fourier Transform (FFT) function.

This process permitted a means for WIL to meaningfully quantify intensity of wrist movement and permit the examination of three tempo-dependent loading (work) characteristics of wrist movement: 1) the torque due to movement, 2) motor strategy distribution of torque (flex/ext and rad/uln), and 3) performance strategies that might be complementary between left and right wrists.

IML frequency was defined as the number of times that WIL exceeded the CV for each trial. IML frequency was employed as a way to measure and evaluate workload distribution. The presence of tempo-dependent changes in IML frequency provided opportunity to examine how each performer employed alternative motor strategies to decrease work as the demands of the protocol challenged their functional limits. When and how this is accomplished reveals information about motor strategies preferred by each performer.

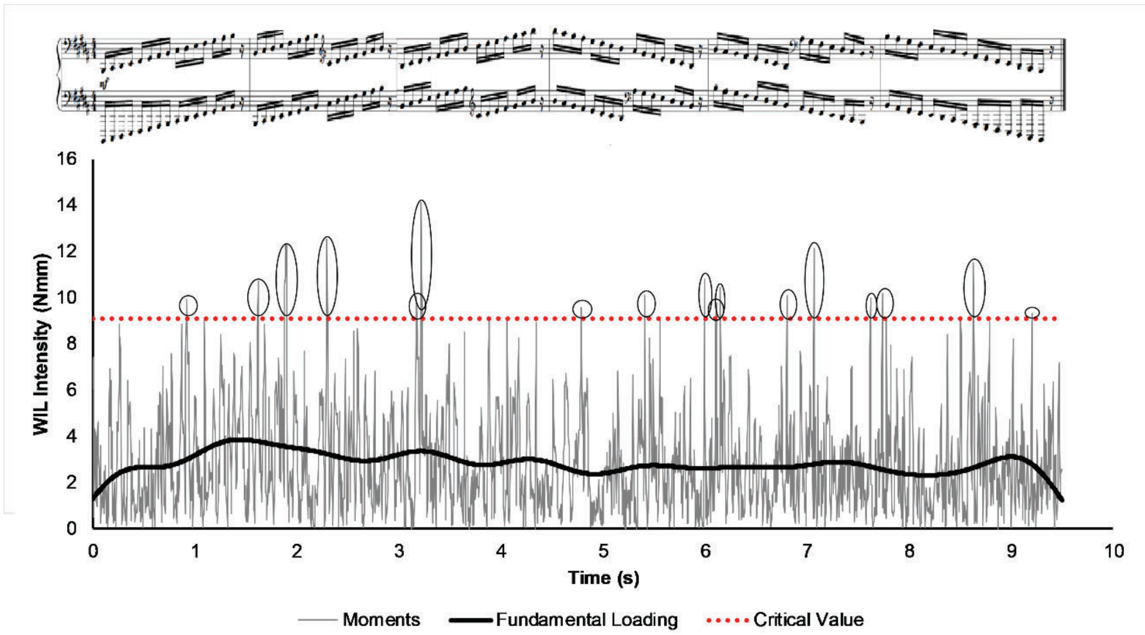


Figure 2: FL, IML, and CV for a single trial at 10N/s. The FL and CV are equal to 2.66Nmm and 9.09Nmm, respectively. The short duration circled peaks represent the IML.

2.3 RESULTS

2.3.1 ANTHROPOMETRIC AND MOBILITY TESTING

The two subjects tested were anthropometrically different from each other. The male was significantly taller than the female (1.9m and 1.645m, respectively) and hand span, hand length, forearm length, and upper arm length were greater for the male (hand span: 20.3 cm; hand length: 21.9 cm; forearm length: 27.0 cm; upper arm length: 33.1

cm) than the female (hand span: 17.8 cm; hand length: 17.2 cm; forearm length: 25.3 cm; upper arm length: 28.9 cm). Wrist ROM was greater for the female than for the male (R(flex/ext) 93.3° vs 89.8°; R(rad/uln) 43.0° vs 21.1°; L(flex/ext) 126.7° vs 103.5°; L(rad/uln) 52.5° vs 30.5°). For both participants, the left wrist had a greater ROM than the right.

2.3.2 WIL INTENSITY

Inverse dynamic analysis revealed two types of WIL. WIL data points above the 70% CV were identified as Impact loads (IMLs) (circled peaks in Figure 2). These were due to abrupt changes in wrist movement (Visentin & Shan, 2003).

Load intensity was low for both subjects, a finding which was expected given the nature of the task (for example, wrist torque during tennis is 50x greater than those found in the current piano performance study) (Bahamonde & Knudson, 2003). Table 1 identifies WIL intensity and IML Frequency at all tempi for all planes of wrist movement (right and left wrists).

Table 1: WIL intensity and IML Frequency as a function of tempo in all planes of wrist movement (both wrists).

		Female		Male	
Tempo (Notes/second)	Wrist Plane of Movement	WIL Intensity (Nmm)	IML Frequency: Individual Planes of Movement	WIL Intensity (Nmm)	IML Frequency: Individual Planes of Movement
4	R(flex/ext)	0.83	20	2.38	19
	R(rad/uln)	1.30	23	1.91	19
	L(flex/ext)	0.85	15	2.07	26
	L(rad/uln)	1.27	22	1.81	15
6	R(flex/ext)	1.01	18	3.48	38
	R(rad/uln)	1.49	25	2.62	9
	L(flex/ext)	1.20	17	2.94	8
	L(rad/uln)	1.50	10	2.57	9
8	R(flex/ext)	1.38	9	3.36	30
	R(rad/uln)	1.9	15	3.08	10
	L(flex/ext)	1.48	25	2.97	18
	L(rad/uln)	2.00	10	3.06	21
9	R(flex/ext)	1.52	12	3.35	24
	R(rad/uln)	2.03	33	3.36	13
	L(flex/ext)	1.64	15	2.99	9
	L(rad/uln)	2.20	9	3.34	16
10	R(flex/ext)	1.19	11	2.87	19
	R(rad/uln)	1.43	20	3.27	8
	L(flex/ext)	1.91	17	3.36	9
	L(rad/uln)	2.43	23	3.72	18

Note: A Newton millimetre is a unit of torque equal to the force of one Newton being applied to a moment arm which is 1mm long.

WIL intensity for left and right wrists of each performer as a function of tempo is shown in figure 3. Loading was consistently greater for the male (1.81 to 3.72Nmm) than for the female (0.85 to 2.43Nmm). For both performers, left WIL increased steadily as tempo became faster. For the right WIL, intensity increased for both performers until 9 N/s, where it started to decrease.

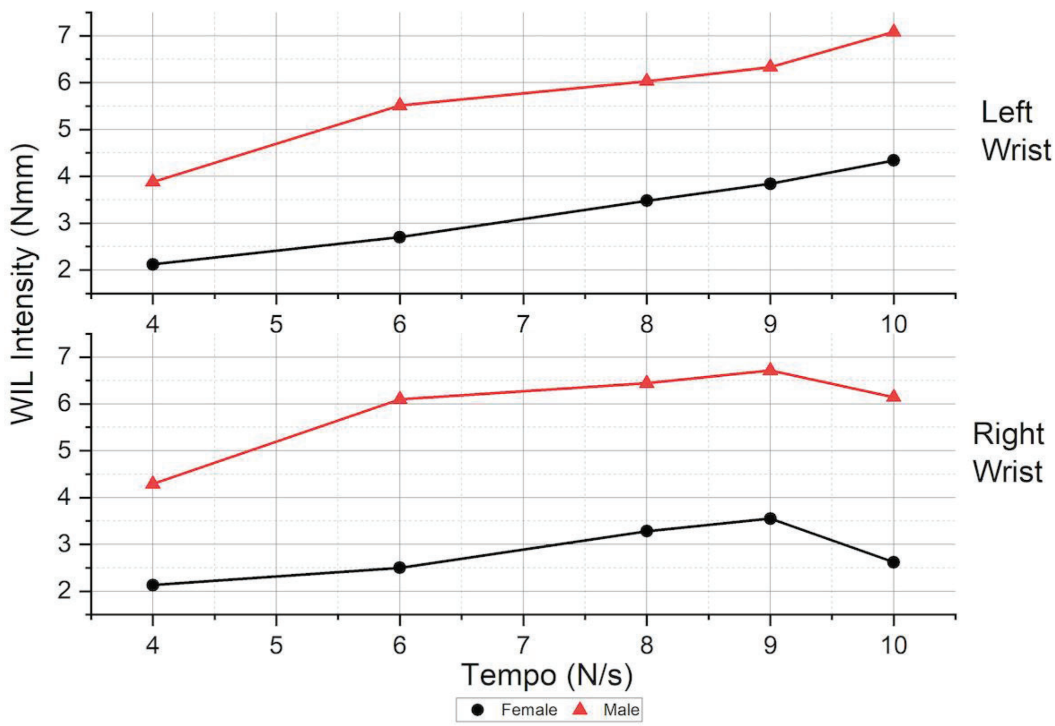


Figure 3: Left and right WIL intensity (totals of rad/uln and flex/ext) for the female and male pianists as a function of tempo.

An examination of WIL intensity broken into requisite components (rad/uln and flex/ext) as a function of tempo is shown in figure 4. For the female, across all tempi, WIL intensity was consistently greater for rad/uln than flex/ext in both wrists. Intensity increased steadily as tempi increased except at the very fastest tempo (10N/s) where intensity sharply dropped for both R(rad/uln) and R(flex/ext.). For the male, intensity in both wrists was greater for flex/ext than for rad/uln at slower tempi, and was lesser at the fastest tempo. Also, for the male, rad/uln increased for both wrists as tempo increased; flex/ext, however, increased only briefly, plateauing at 6N/s. At the highest tempo WIL intensity of the right hand decreased (both planes of movement) while WIL for the left hand increased for both performers.

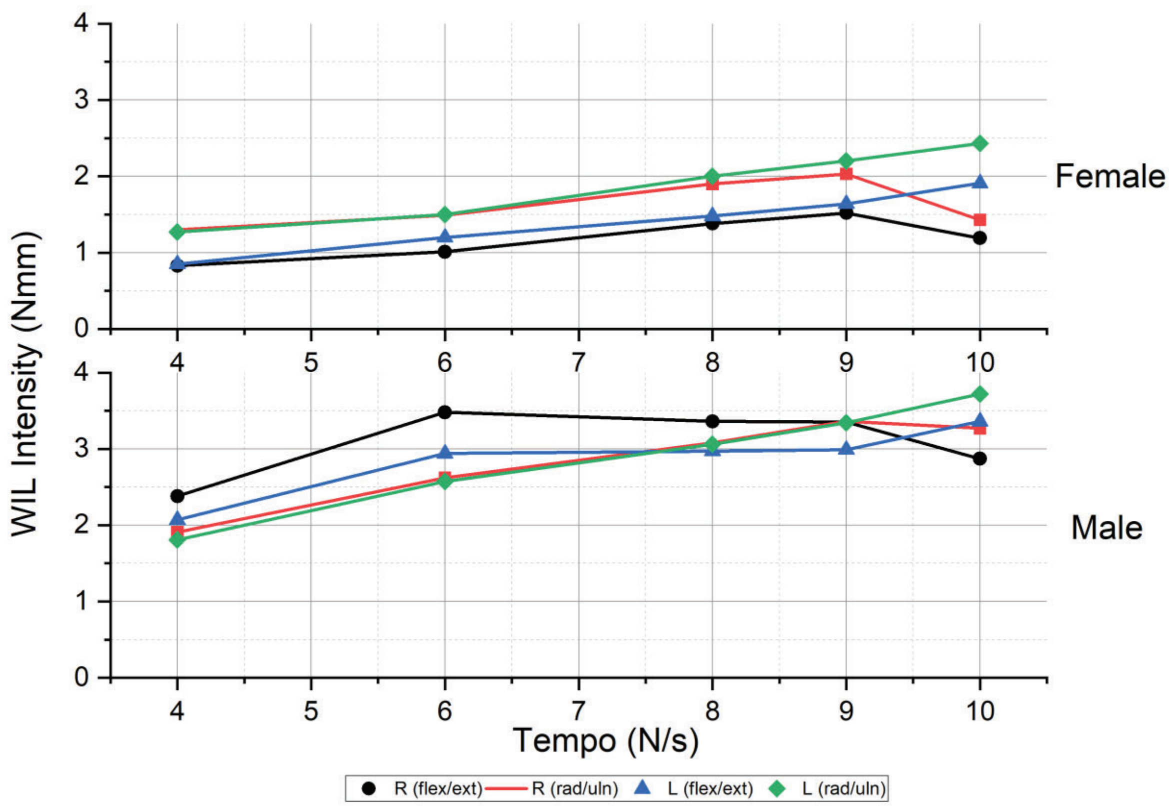


Figure 4: The female and male pianist's WIL intensity in the x and y planes of both wrists as a function of tempo.

2.3.3 IML FREQUENCY

Across the tempi tested, variation in IML frequency (all planes of movement) reveals distinct profiles for each of the subjects. IML frequency totals (sum of flex/ext and rad/uln for each wrist) and averages as a function of tempo are shown in figure 5 (top row). For the female performer, the average IML decreased from the slowest tempo until 8N/s, after which it began to increase. As well, left and right wrist IMLs are alternatingly high from 6N/s to 10N/s. For the male performer, except at the slowest tempo (4N/s), the right wrist always exhibited higher IML frequencies than the left. His average IML remained virtually unchanged from 4-8N/s, whereafter it began to decrease.

Figure 5 (bottom row) shows IML intensity broken into requisite components (rad/uln and flex/ext) as a function of tempo. For the female, IML frequency varied more for rad/uln deviation than for flex/ext in both wrists; right wrist rad/uln IML frequency varied from 15 to a peak 33 and the left wrist rad/uln IML frequency varied from 9 to 23. In both cases, greatest rate of change (steepest slope) occurred at higher tempi. For the male, the opposite holds true. IML frequency varied more for flex/ext than for rad/uln deviation in both wrists; right wrist flex/ext IML frequency varied from 19 to a peak 38 and the left wrist flex/ext IML frequency varied from 9 to 26. IML frequency for L(flex/ext) generally decreased as tempi became faster. For R(flex/ext) there was a sudden increase in IML frequency between 4 to 6 N/s that was followed by decreases at all other tempi.

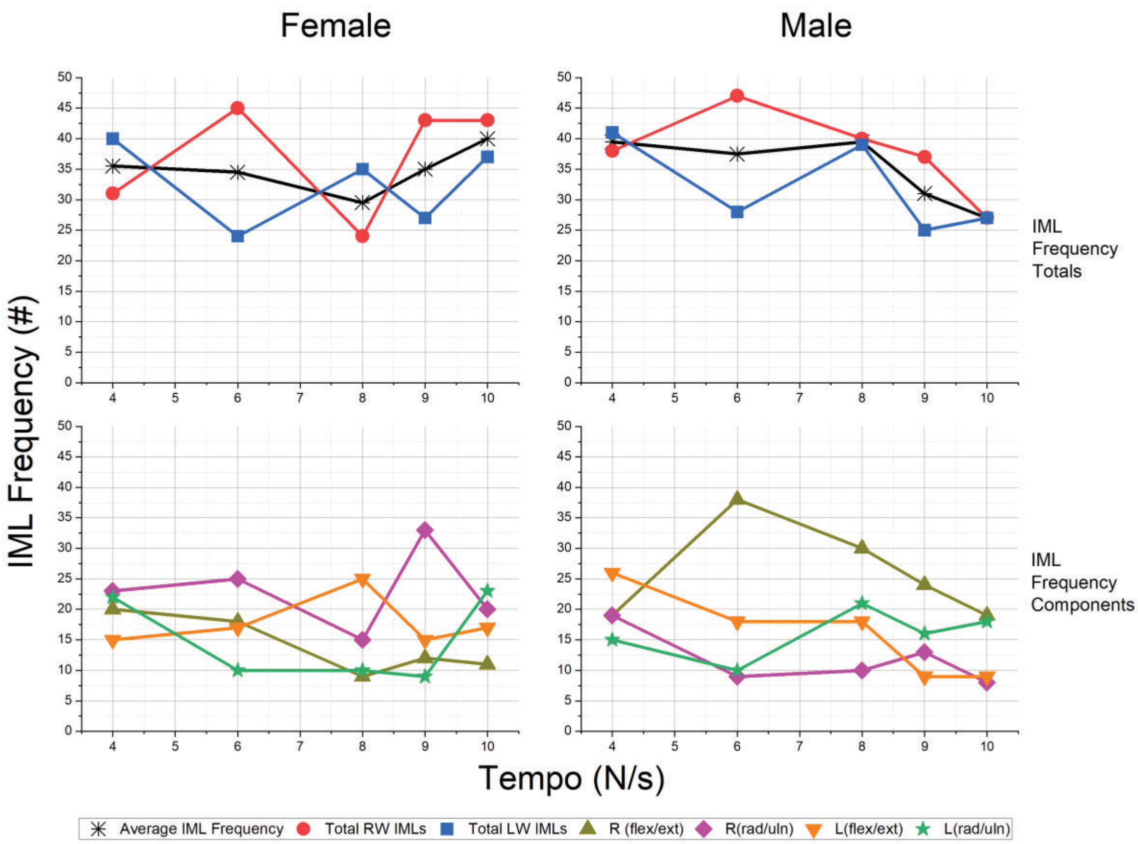


Figure 5: The female and male pianist's IML frequency totals (the sum of flex/ext and rad/uln for each wrist) and the average IML frequency for both wrists (first row). The female and male pianist's IML frequency components (flex/ext and rad/uln) in the wrists as a function of tempo are shown in the bottom row.

2.4 DISCUSSION

In the current study, tempo was an independent variable, which permitted observation of alternative motor behaviours invoked by study participants to accommodate changes in playing speed. As a case comparison, the large difference in physical statures of the two subjects provides a means to consider results in terms of ergonomics and anthropometric capacity. This study begins a process of documenting the relevance of compensatory strategies, based in applied biomechanics, for music performance.

2.4.1 WIL INTENSITY

From a performer's perspective, reduction of movements that serve no purpose in forwarding musical outcomes has practical benefits: 1) extraneous movements undermine fine motor skill accuracy and repeatability, making the control of outcomes more taxing than necessary, and 2) since the development of PRMPs has been shown to be related to loading type, loading intensity, and duration of activity (Visentin & Shan, 2004) minimizations of physical effort should result in a reduction of injuries. The motor task of the protocol required participants to execute between 480 (slowest tempo) and 1200 (fastest tempo) keystrokes per minute using both hands moving mediolaterally over a keyboard distance of 84.5 cm. The fine motor behaviour and intensity demands of this protocol clearly challenge the limits of human capacity; the difficulty is in finding parameters that meaningfully characterize performers' responses to these challenges.

In the present study, WIL was used to quantify intensity of wrist movement. The male subject's generally higher WIL, in both wrists, may be explained as a reality of the physics of movement; for the same angular acceleration, his larger hand, with a greater moment of inertia than her smaller hand, results in higher WIL. Total WIL (left and right wrists) as a function of tempo (Figure 3) revealed near-identical contours for each performer. As might be expected, left WIL increased linearly as the difficulty of the task increased due to faster tempi. However, for the right wrist, WIL decreased at the fastest tempo, which seems to indicate both performers were attempting to find efficiencies as a means of decreasing playing difficulty. Notwithstanding subjects' very different anthropometrics, this intensity reduction “strategy " occurred for both at the same tempo, and only in the right wrist. Since both pianists were right-hand dominant, it seems intuitively reasonable that dominant-hand motor behaviour strategies might be a “first recourse” to reduce effort (Kopiez et al., 2012).

Although hand dominance might explain right-hand WIL decreases at the fastest tempo, it does not explain the individualized strategies used by each subject – anthropometry might. When looking at individual planes of wrist movement, WIL intensity (right and left wrists) was highest in rad/uln for the female and highest in flex/ext for the male, suggesting hand size might be a factor contributing to motor behaviour strategy selection. A greater use of rad/uln increases medial-lateral reach on the piano keys, something not needed by the male subject because of his larger hand size. For the female pianist (Figure 4, top row), effort reduction in the wrists was accomplished through efficiency gains in both flex/ext and rad/uln WIL components. For the male pianist (Figure 4, bottom row), most of the effect was accomplished by reducing WIL in flex/ext. Given the female pianist’s reliance on rad/uln as a means to expand medial-lateral reach, manipulation of this component may have provided more “room” for effort reductions. For the male pianist, because he employed greater amounts of flex/ext than rad/uln deviation, there was more utility in manipulating flex/ext as an effort reduction strategy.

2.4.2 IML FREQUENCY

For a task where motor training requires long hours of repetition (like playing the piano), it is rational to avoid working harder than is necessary; workload efficiencies enable longer periods of better practicing and learning. In the present study, IML frequency was employed as a way to measure and evaluate workload distribution and discuss the effects that anthropometry may have on some of the differences observed between subjects. At 8N/s, the female's average IML frequency started to increase while the male's decreased (Figure 5, top row). For the two pianists, 8N/s might have been a threshold where the difficulty of the task necessitated a switch in motor behaviour strategy to optimize movement efficiency. The male utilized an efficiency optimization strategy where IML frequency in both wrists was refined in order to mitigate additional effort caused by increases in tempo. For the female, increases in average IML frequency above 8 N/s might indicate that due to a smaller hand size, the efficiency optimization strategy of reducing IML frequency at faster tempi was harder to come by (Lai et al., 2015; van Vugt et al., 2014). Looking at the left and right wrists individually, IML distribution between the wrists seems to alternate for the female pianist (Figure 5, top left). This might indicate an effort reduction strategy involving an alternating focus on different hands. For the male pianist, the right wrist was always more active than the left (Figure 5, top right) and the left wrist IML was more highly variable, which suggests the dominant hand to have been the stabilizing influence.

When looking at individual planes of wrist movement, for the female, IML frequency varied more for rad/uln deviation than for flex/ext in each wrist (Figure 5, bottom left). Simply, rad/uln was being used in greater capacity than flex/ext when responding to tempo-driven increases in work/effort. For both wrists, rad/uln showed greatest rates of change (steepest slopes) and greatest fluctuation at higher tempi.

Between 9 and 10 N/s, IML increased, indicating the tempo at which the task became substantially more challenging. In the right wrist, the female pianist employed a rad/uln dominant wrist movement strategy to accomplish the task of lowering high IML frequencies at 10 N/s. In the left wrist, rad/uln increased markedly from 9-10 N/s after having been at very low levels between 6 and 9 N/s. Handedness could explain this behaviour; for our right-handed subjects a non-dominant hand might work harder because there tends to be a greater emphasis on right hand technique in piano performance (Kopiez et al., 2012).

For the male, IML frequency varied more for flex/ext than for rad/uln in each wrist (Figure 5, bottom right). Thus, flex/ext was the primary component of movement used to respond to tempo-driven increases in work/effort. For the right wrist, IML frequency (flex/ext) increased between the two slowest tempi, a result that might indicate the performer to have been paying less attention to the use of his motor resources since the task at these tempi was still simple. Above 6 N/s IML frequency (flex/ext) showed steady decreases for both wrists, indicating a steady refinement of flex/ext in response to increases in task difficulty; at these speeds the male pianist employed a flex/ext dominant wrist movement strategy to refine wrist movement as tempo increased.

When a tool is employed during any performative task, an individual's anthropometry is a central determinant of the range of motor possibilities available to execute that task (Ballreich, 1996). Playing the piano requires motor manipulation of an instrument that has fixed dimensions and is immobile during performance (Turner et al., 2021). Unlike instruments that are held by hand, such as the violin, the position of the piano cannot be adjusted during a performance to accommodate transitory motor needs of a performer; the performer must adjust to the instrument. This fact and a performer's anthropometry influence both the number and type of motor strategies available to effect desired musical outcomes; every performer, through years of motor training, develops a hierarchy of motor strategies to employ in the service of optimizing his/her performance. In all practicality, this means that there is no universally "correct" way to play the piano but, depending on musical context, there may be some strategies that are "better" for reducing effort.

Thus, understanding that motor strategies are linked to anthropometry has broad ranging implications. First, it may suggest more efficient approaches to pedagogy. Modeling is employed extensively in music pedagogy; however, applied anatomy and biomechanics are not standard subject matter in music training (Wijsman & Ackermann, 2019). Hence much of this modeling involves demonstrating musical outcomes and the mechanical means that the teacher has found to affect those outcomes. In the absence of a conscious and reasoned understanding of alternative motor strategies, a teacher can only model physical behaviours which come from their personal experience (Visentin et al., 2008). Awareness of alternative motor strategies may help an educator model more effectively for each student and, further, lend him/her a vocabulary to clearly explicate these alternatives. By directing students through a range of motor strategies best suited to their anthropometry, it seems reasonable to think that teachers could accelerate the learning process and improve musical outcomes. At the very least, by having several alternative motor strategies consciously rationalized, a teacher has an increased repertoire of starting points for imparting new skills to students. Second, in an industry where PRMP are prevalent, any effort invested in increasing learning efficiency has the potential to reduce injury rates. Rationalizing objectifiable parameters in terms of anthropometric potentials is a first step in addressing these issues.

2.4.3 LIMITATIONS AND FUTURE SUGGESTIONS

The current study analyzes motor behaviours of two pianists, one taller and one shorter, in order to begin the process of examining anthropometrically driven alternative compensatory behaviours and behavioural strategy selection during piano performance. As such, it documents a limited number of compensatory behaviours available to pianists; other equally successful strategies may exist. Inferences about cause and effect should be understood as speculative until a larger body of research is available for pianists of varying anthropometry. The standardized protocol was chosen to limit interpretive variability that would normally be expected when performing in a concert setting. Hence, it measured a defined task and not the full range of the task's malleability. To do so the current study focused only on wrist kinetics and a more extensive examination of upper limbs might reveal additional compensatory mechanisms.

2.5 CONCLUSION

Performing the piano at expert levels requires long-term training. Throughout this training, many aspects of "playing technique" become subliminal for the performer, yet they are available for manipulation when circumstances and artistry so require. Since a piano keyboard is of fixed dimensions, anthropometric differences between individuals result in different performers having different performance-strategy options. The current study begins the process of documenting a range of motor behaviours that can be called upon during piano performance. It does so by employing a case comparison to explore the utility of analysing wrist kinetics for a standardized piano performance task. The objective was to 1) observe similarities and differences in motor behaviour/strategy between two expert performers, and 2) discuss observed results in terms of performers' notably different anthropometry. In the current study, wrist internal loading (WIL) and impact loading (IML) frequency were used to examine tempo-dependent loading and to measure both workload distribution and effort reduction strategies in the wrists during performance.

WIL and IML changes throughout the protocol both suggest that anthropometry and handedness might play a role in wrist effort reduction strategies. Both WIL intensity and IML frequency showed that, as task difficulty increased, changes in motor behaviour/performance strategy occurred at faster speeds for both expert performers. Further the non-dominant wrist became more variable as the task became more difficult. For both performers, manipulation of IML frequency appears to be a prime strategy for reducing wrist effort as tempo of the protocol increased and the task became more difficult.

This study is the first to investigate pianists' wrist kinetics in terms of ergonomics and anthropometry. It sets the stage for future research by providing a framework for further examinations of effort-reducing piano performance strategies throughout the kinetic chain. The underlying hypothesis of the current research is that, since anthropometry varies from individual to individual, the identification of anthropometrically empathetic motor behaviour strategies can improve pedagogical practice. This has the potential to help performers optimize physical effort to prevent PRMP while simultaneously increasing the expressive vocabulary available to performers through the conscious manipulation of alternative motor strategies. Without improvements in current teaching and performance modeling practices, one can only expect existing rates of PRMP to continue. A systematic translation of biomechanical, anthropometrical, and ergonomic understanding into music teaching is needed so that learners may strive for musical excellence without compromising their musculoskeletal health.

CHAPTER 3: PURSUING ARTFUL MOVEMENT SCIENCE IN MUSIC PERFORMANCE: SINGLE SUBJECT MOTOR ANALYSIS WITH TWO ELITE PIANISTS

Note – the contents of this study are published in:

Turner, C., Visentin, P., Oye, D., Rathwell, S., & Shan, G. (2021a). Pursuing artful movement science in music performance: single subject motor analysis with two elite pianists. *Perceptual and Motor Skills, 128*(3), 1252-1274. https://doi.org/10.1177/00315125211003493

3.1 INTRODUCTION

Instrumental music performance ranks among the most complex of learned human behaviours (Visentin et al., 2015). For example, a professional pianist performing the 11th variation of Franz Liszt's 6th Paganini-Etude must play up to 1800 notes per minute for some sections of the music (Münte et al., 2002). Performing in a Wagner opera can take 4.5 hours (Wagner, 1868). Given the physical intensity, low tolerance for errors, and high endurance requirements of music performance, it has been categorized by many as an athletic endeavour (Dick et al., 2013; Quarrier, 1993). However, unlike athletes, musicians typically receive little or no education regarding the most effective ways to prepare their bodies and minds for the rigors of performance (Wijsman & Ackermann, 2019). Rather, instruction in the mechanics of playing an instrument is typically based primarily on a teacher's experience. The quantitative literature in human movement science pertaining to music pedagogy and motor learning is only now beginning to emerge (D'Amato et al., 2020; Furuya & Altenmüller, 2013; Visentin et al., 2015).

The dearth of human movement research in music instruction may be explained in part by cultural norms in the music discipline. Even today, most western classical music pedagogy relies upon centuries-old, tradition-based, master-pupil teaching strategies that are, for the most part, only nominally systematic (Purser, 2005; Norton et al., 2015; Visentin et al., 2015). Although this model of pedagogy has offered benefits of individualized training, so strong a reliance on teachers' personal perceptions of their own experiences has pedagogical limitations. Another reason for scarce motor learning research in music training is likely an artifact of disciplinary and cultural boundaries in human movement science. With its origins in sports analysis and daily living activities, human movement science methods and analytic techniques are best suited for examining movement repeatability. Yet, at its most artistic, music performance, like the highest levels of sports performance, is an act of interpretation and perhaps even improvisation, not one of reproduction or utility (Cook, 2014; Palmer, 1997; Shan & Visentin, 2010). Outcomes in music performance are intentionally manipulated toward artistic expression. For musicians, a failure to consider musical context when analyzing underlying motor behaviours renders research pointless for real-world applications. For human movement scientists, artistic manipulation of context can be a nearly insurmountable confounding factor in experimental designs and data analysis (Shan et al., 2007). This makes applying human movement research methodologies to motor learning when playing a musical instrument very challenging. If music performance is the central object of study, music motor behaviour research must become more "artful" in its analytic motivation and methods so that research design informs artistry rather than merely describing performance gestures.

Despite seeming incompatibilities between music performance instruction and human movement science to date, there is a small but growing body of research that has applied human movement science methods to music performance (Baadjou et al., 2017; Ferrario et al., 2007; Hopper et al., 2017; Rickert et al., 2013; Shan & Visentin, 2010; Visentin et al., 2008). Because music performance is a task with high perceptual motor demands, a musician's gross and fine motor control are visibly co- and inter-dependent, notwithstanding intentional artistic interpretive variability (Shan et al., 2013). Thus, elite musicians must learn a variety of fundamental motor movements and strategies, and practice manipulating them, in order to render performances that are novel while still falling within expectations of musico-cultural traditions. Motor learning research has the potential to accelerate motor learning by informing traditional experience-based pedagogical methods with scientific analysis and objective reasoning, so long as science remains sensitive to musical performance demands. Although the existing literature has shown, in principle, that human movement science methods have analytic utility for describing elements of music performance, the next step in applying human movement science to music instruction must be to demonstrate goals of artistic flexibility are not encumbered by limitations of experimental research design.

For improving piano performance, most biomechanical and motor behaviour research to date has employed protocols that emphasize reductionistic keystroke exercises (Furuya & Kinoshita, 2008; Degrave et al., 2020; Oku & Furuya, 2017; Verdugo et al., 2020). Some have used scales, which are mechanical exercises designed to develop a pianist's technique (Ferrario et al., 2007; van Vugt et al., 2012, 2014). A smaller number of studies have examined piano performance in the context of musical excerpts. Most of these have controlled performance variability by instructing performers in "how" to perform the music so that non-expressive and expressive performances can be distinguished (Castellano et al., 2008; Thompson & Luck, 2012; Massie-Laberge, et al., 2018a; Massie-Laberge, et al., 2018b). The methodologies of these studies have illuminated some of the mechanical demands of piano performance, but they have not addressed artistic demands because they have restricted or modified performers' subconscious musical intentions and, concomitantly, the motor behaviours associated with them. Although researchers highly value controls over variability beyond factors of primary interest, the reality of concert performance is that the musical context drives performance variables; individual musical intention necessarily influences the selection of specific motor behaviours.

From a biomechanical perspective, anthropometry is important when learning a skill. Interestingly, with the exception of research on hand span and ergonomically modified keyboards (Booker & Boyle, 2011; Boyle et al., 2015; Chi et al., 2020; Deahl & Wristen, 2017; Farias et al., 2002; Lai et al., 2015; Wagner, 1988; Wristen et al., 2006; Yoshimura & Chesky, 2009), anthropometry has been overlooked in existing biomechanics research on piano performance and music pedagogy. Factors suggesting a need for more attention to anthropometry include these: (a) the keyboard is immobile and of fixed dimensions, (b) pianists must play notes according to directives in the musical score, and (c) anthropometry is largely a fixed variable for each pianist who must individualize positioning and repositioning the body to facilitate how fingers address the keyboard during performance. Within this individualization, some generalizable trends may exist.

Developing motor learning strategies that are appropriate for an individual's anthropometry will ultimately allow pianists to optimize their performance outcomes (i.e., achieve autonomous motor learning sooner) (Fitts & Posner, 1967). Given the significance of gross motor movement on fine motor execution and that pianists' gross motor movements have been understudied, we aimed, in this study, to address anthropometry and musical context for pianists' gross motor behaviours. One of the few studies in this realm analyzed trunk motion in pianists (Verdugo et al., 2020), another analyzed hip kinetics (Massie-Laberge, et al., 2018b), and several recognized core balance/center of gravity (COG) as an important factor in piano performance (Koga & Nogami, 2012; Wristen, 2000; Zhang, 2020). Drawing on this preceding research, we examined two elite pianists' motor behaviours during a complex musical performance so as to quantify pianists' joint activity in the trunk, shoulders, elbows, and wrists and their dynamic balance shifts in COG. In our discussion of observed results, we then considered the individual anthropometric and musical drivers that may have motivated their motor strategies.

3.2 METHOD

3.2.1 PARTICIPANTS

In this multiple single subject analysis, we recruited two anthropometrically different, right-handed, expert pianists as study participants (one female and one male). Participant 1 (A) was 1.6 meters tall and Participant 2 (B) was 1.9 meters tall. Neither participant was hypermobile (Beighton Hypermobility protocol). Both pianists held doctoral degrees in piano performance and were informed of the data collection procedures and research protocol prior to providing their written informed consent

(University of Lethbridge Human Subject Research Committee approval #2018-098).

3.2.2 MATERIALS

A ten-camera 3 D motion capture system (VICON MX40, Oxford, England) was used. Thirty-nine reflective markers were placed on the participants in accordance with a 15-segment full-body biomechanical model. From positional data, this model permitted joint angle and range of motion (ROM) quantification of the pelvis (trunk/spinal movement), shoulder (the glenohumeral joint), elbow, and wrist (Figure 6). Data was recorded at 200 frames/s with a calibration error of <0.6 mm. Marker placements were: four on the head, nine on the trunk (sternal end of the clavicle, xiphoid process, C7, T10, right scapula, and the right and left anterior superior iliac and posterior superior iliac), 14 on the upper extremities (the left and right acromion, lateral side of the humerus, lateral epicondyle, lateral side of the forearm, radial styloid process, ulnar styloid process, and 3rd metacarpal), and 12 on the lower extremities (the left and right lateral side of the thigh, lateral tibial condyle, lateral side of the shank, lateral malleolus, calcaneus, and distal end of the hallux). Participants wore a specialized garment that permitted secure marker placement without impeding movement. Additionally, 88 markers were placed on both white and black piano keys to identify keystroke accuracy.

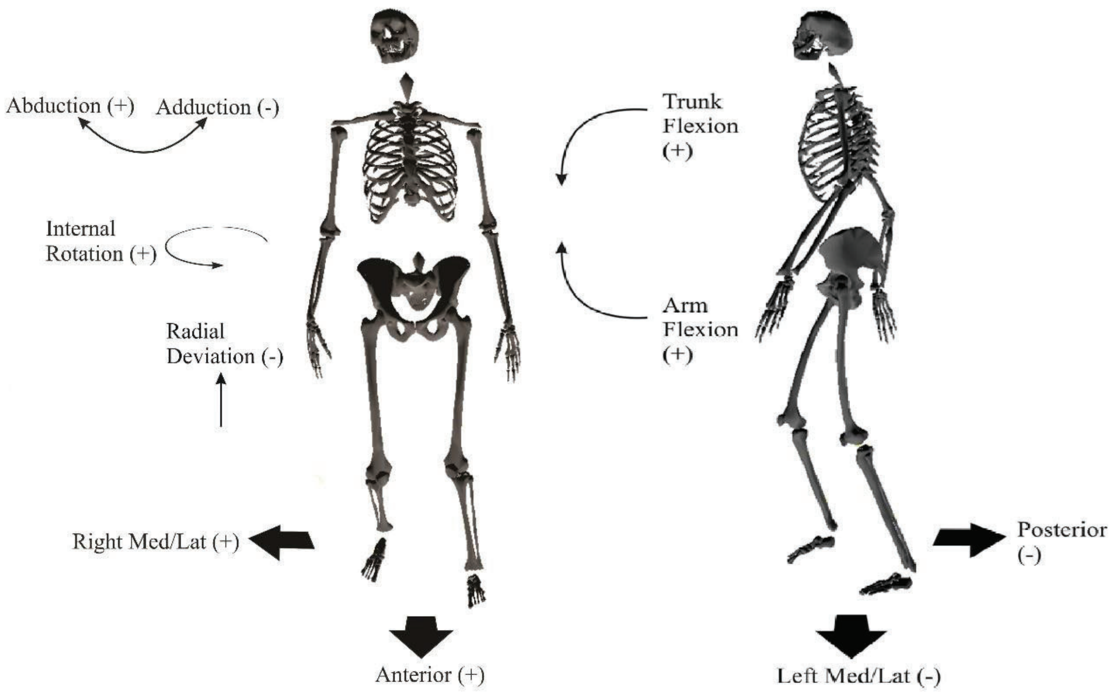


Figure 6: Upper Arm, Trunk, and COG Neutral Positions for the pianists. Note: Trunk (spinal) flexion, shoulder flexion, abduction, internal rotation, elbow flexion, wrist flexion, and ulnar deviation are positive angles. COG excursions that are anterior and to the right (upper end of the keyboard) are positive.

We placed a Kistler force plate (1 N, Swiss; 60 cm x 40 cm) under the piano bench to measure the participants' anterior/posterior (ant/post) and medial/lateral (med/lat) COG shifts. Force plate data employed the center of the plate as the origin for COG measurements, and was synchronized with motion capture data. Figure 7 shows the experimental set-up and illustrates a sample frame from the computer-generated participant and keyboard models.

Figure 7: The Experimental Set-up (left), with Markers placed on the Participant and Keyboard (top right), and a Sample Frame from the Computer-generated Model (bottom right).

3.2.3 MUSICAL EXCERPT

Participants performed the first six measures of Chopin's "Revolutionary" Etude Op. 10, No. 12 (Figure 8). Participants were given the music two weeks prior to data collection and were not required to memorize the musical excerpt. Both participants had the music available to them during data collection however, based on visual observation, neither were reading from the score when performing. This excerpt was chosen because it is extremely difficult, and the musical context demanded a variety of motor skills. This also naturally divides into three parts (P1, P2, and P3), demarked by two critical points where discontinuous leaps from the low to high registers of the piano occur (Figure 8, dotted lines). For the left hand (bottom notes on each musical stave), motor demands are continuous throughout all segments. For the right hand (top notes on each stave), motor demands are tripartite in P1 and P2, with playing a chord two beats in length, resting (periods where the hand is not playing any notes) five beats in length, and a "pickup" or leading gesture into the next segment, one beat in length. In P3, the right hand mimics the general pattern of the left hand. These motor skills, both symmetric and asymmetric, required highly developed motor coordination between both limbs, something that is achieved through long-term training (Kilincer et al., 2019).

Unlike many other activities involving keystroke manipulation (such as typing at a computer keyboard), playing legato (smoothly) at the piano requires precise coordination of the downward movement of one finger (to sound a note) with the upward movement of another (to stop the note that is already sounding). Chopin's musical directives required an allegro con fuoco (fast with fire) tempo (playing speed), legatissimo (the smoothest possible) articulation, a forte (loud) volume, accents (>) on specified notes, localized crescendi (increases in volume), and chordal structures requiring simultaneous use of four or five fingers of the right hand.

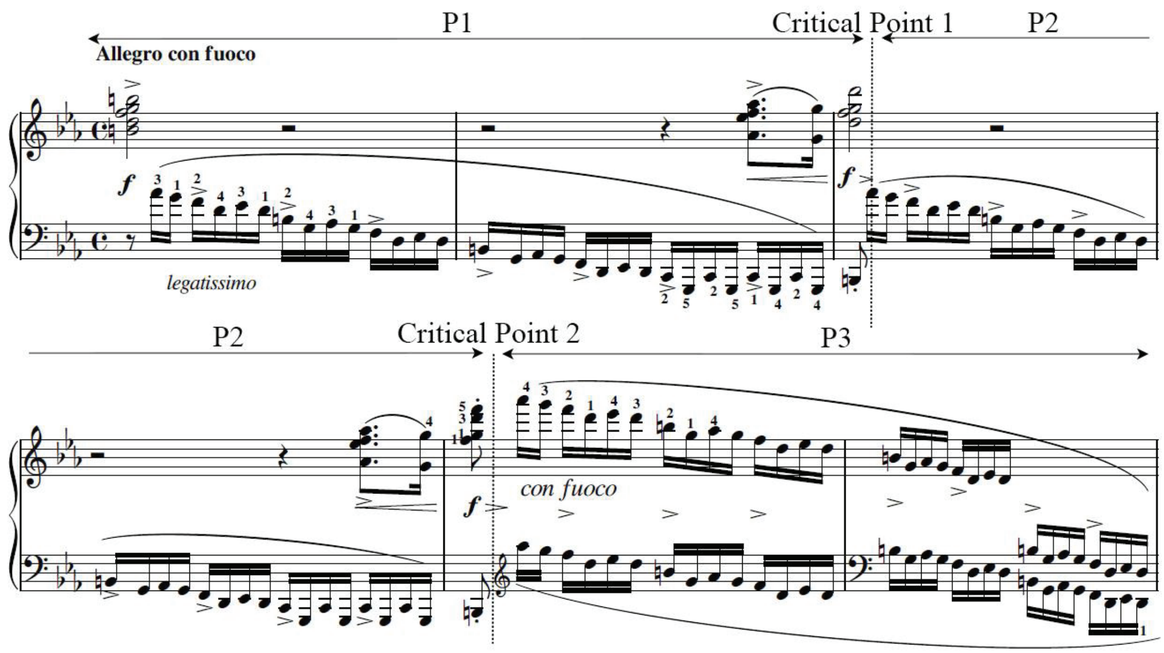


Figure 8: The First Six Measures of Chopin's Op. 10, No. 12 ("Revolutionary Etude") Performed by the Participants. Note: The vertical lines (critical points) indicate the moment when the pianist must shift across the keyboard. P1, P2, and P3 are labelled accordingly.

In the current study, performance tempo was controlled at 135 beats per minute (bpm), using a metronome and participants were not permitted to use the pedals. No other musical controls were implemented in the study, which allowed the participants artistic freedom. Since four notes per beat are required in this composition, resultant playing speed was 540 notes/min or roughly 9 notes/s (N/s). At this tempo, the musical excerpt was fast enough (110 ms per keystroke during the 16th notes) that performers could not possibly execute each note as an individual gesture. According to Rottondi et al. (2016), variability in musical timing below 20 ms is perceived by listeners as highly coordinated, and according to Kazennikov and Wiesendanger (2009), differences between 60 and 100 ms are perceived as errors in timing. Considering these constraints, the musical excerpt of the current protocol left performers virtually no room for error.

3.2.4 PROCEDURE

Participants performed on a 9-foot New York Steinway grand piano in a concert hall setting. Unlike artificial keyboards/digital pianos where significantly less force is required to depress a key and tone quality may be compromised due to electronic sound production (Meinke, 1995), a Steinway grand piano is generally accepted as an ideal concert performance instrument for professional pianists. Subjects were permitted to warm-up and adjust bench height/position according to personal preference. Anthropometric measurements (body height, body mass, leg length, ankle and knee width, shoulder offset, elbow and wrist width, and hand thickness) were documented prior to testing for the purposes of biomechanical modeling.

3.2.5 DATA PROCESSING AND ANALYSIS

We used a 15-segment biomechanical model to process raw kinematic data with VICON Nexus Software. The model employed a rigid-body system with multiple segments: head, upper trunk, lower trunk, upper arms, forearms, hands, thighs, shanks, and feet. Using established anthropometric norms (Shan & Bohn, 2003; Winter, 1990), we calculated inertial characteristics of segments. We analyzed data with Microsoft Excel software to determine center of gravity (COG), joint angles and joint range of motion (ROM) for the pelvis (trunk), shoulders, elbows, and wrists.

3.3 RESULTS

Table 2 displays the trunk, shoulder, elbow, and wrist ROMs, as well as the COG excursion for both participants. Clearly, each pianist (A and B) utilized a different motor behaviour strategy to perform the excerpt. For nine of the fourteen measured joint angles, A used greater ROM than B. For seven of the fourteen joint angles, the difference was notable (greater than 5, with right shoulder flex/ext differing 28.7). For B, only two joint angles showed notably larger ROM than A (right shoulder abduction/adduction (ab/add) and left wrist flexion/extension (flex/ext)). Five joint angle ROMs were very similar between participants (left shoulder flex/ext and rotation, right shoulder rotation, left elbow flex/ext, and left wrist rad/uln). COG excursion was much larger for A in the medial/lateral (med/lat) plane while it was larger for B in the anterior/ posterior plane (ant/post) (295.0 mm vs 209.6 mm, and 51.1 mm vs 43.0 mm, respectively).

Table 2: Upper body joint angle ROM and COG excursion ROM for both pianists.

		Participant A	Participant B
Trunk (˚)	Ant/Post	**16.2**	10.0
	Med/Lat	**50.9**	36.7
Left Shoulder (˚)	Flex/ext	30.3	30.4
	Ab/Add	**44.7**	36.1
	Rotation	46.2	45.2
Right Shoulder (˚)	Flex/ext	**49.6**	20.9
	Ab/Add	19.0	**27.0**
	Rotation	43.4	46.1
Left Elbow (˚)	Flex/ext	36.6	33.7
Right Elbow (˚)	Flex/ext	**42.5**	26.9
Left Wrist (˚)	Flex/ext	29.6	**39.9**
	Rad/uln	17.0	21.3
Right Wrist (˚)	Flex/ext	**50.5**	30.8
	Rad/uln	**21.8**	13.5
COG (mm)	Ant/Post	43.0	**51.1**
	Med/Lat	**295.0**	209.6

Note: Numbers in bold indicate the subject with the larger ROM in cases where large ROM differences exist.

Figure 9 shows COG ant/post and med/lat excursions (measured from the force plate origin) for each participant. A positioned the bench 10.8 cm closer to the keyboard and 1.1 cm further to the right than B's bench position. A's bench height was approximately 2.8 cm higher than B's bench height. Starting body positions for the performers were also different. A's starting COG position relative to middle C on the keyboard was 0.7 cm closer, 2.3 cm further to the left, and 3.1 cm lower than B's starting COG position (A's coordinates: 20.8 cm, 4.9 cm, 0.2 cm; B's coordinates: 21.5 cm, 7.2

cm, 2.9 cm).

For both participants, changes in COG ant/post were small throughout the musical excerpt, 43.0 mm (A) and 51.1 mm (B) (Figure 9A and B). However, larger movements occurred at the critical points (Figure 9, vertical dotted lines) where discontinuous left-hand leaps were required by the music. This showed both performers to be shifting balance toward the keyboard (Figure 9A and B, circled peaks). With respect to COG med/lat movement (Figure 9C and D), there were large and notable shifts to the right at critical points. COG med/lat excursions (Figure 9C and D, trough to peak) increased for each consecutive section of the music (P1, P2, and P3). COG med/lat excursions for A (Figure 9C, trough to peak) were 86 mm, 136 mm, and 256 mm, respectively. For B (Figure 9D, trough to peak), they were 24 mm, 174 mm, and 199 mm. Notably, at P1 and P2, where the musical demands were nearly identical, A's peak med/lat COG shifts were nearly identical, whereas those for B were not. Both participants utilized a larger med/lat COG shift for the last critical point.

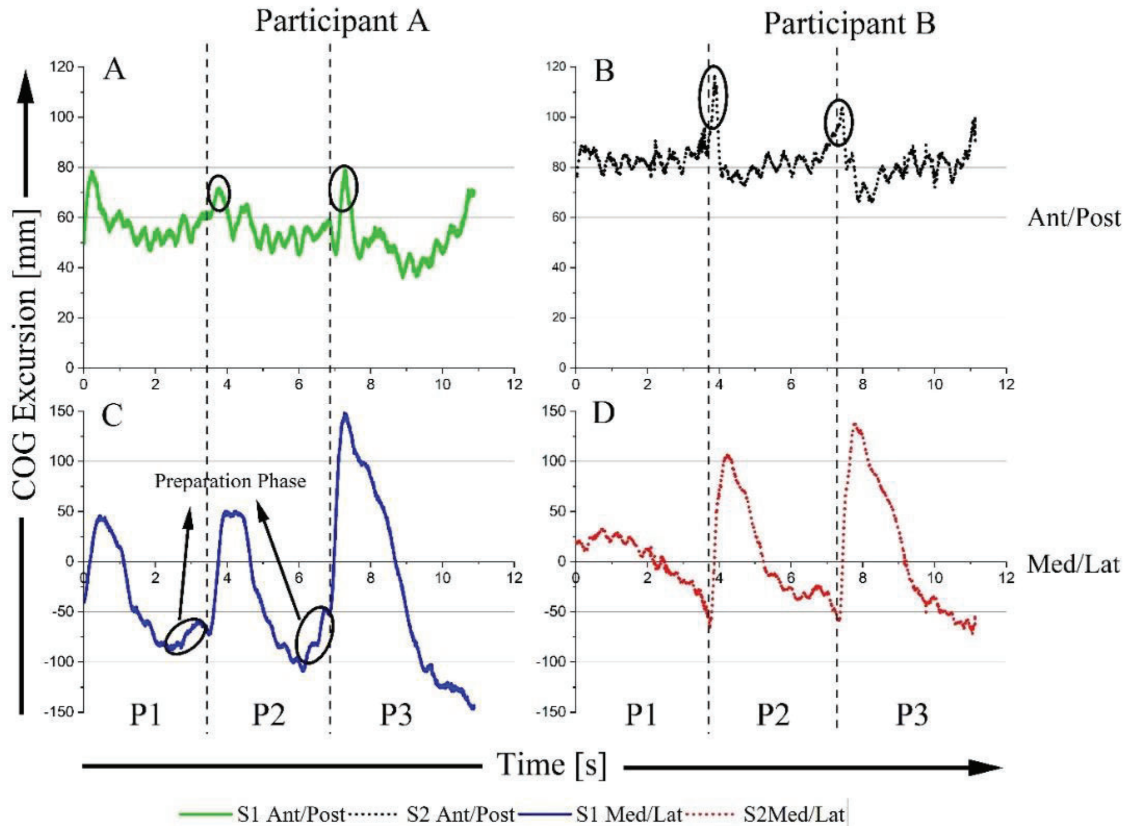


Figure 9: Anterior/Posterior and Medial/Lateral COG Positions as a Function of Time for Both Pianists. Note: An increase in COG excursion represents shifts that are anterior and to the right. In 9A and 9B, circled peaks signify sudden anterior shifts (movement toward the keyboard) corresponding to discontinuous leaps in the music. In 9C, circled areas signify preparation phases.

Figure 10 shows trunk and shoulder joint angles. For both performers, trunk angle graphs reinforce COG excursion findings; trunk movement increased for each consecutive part of the music (P1, P2, and P3). However, unlike COG findings where shifts of balance occurred at critical points and in a discontinuous manner, changes in trunk angle were gradual, controlled, and continuous.

For the left shoulder, participants employed similar motor behaviour strategies. Ab/add and rotation had complementary functionality during P1, P2, and P3; as one increased (or decreased), the other decreased (or increased). Flex/ext cycles for A were wave-like, with peak flexion occurring in the middles of P1 and P2. For B, flex/ext showed a steady progression from greater to lesser flexion in each of P1 and P2. In P3, flex/ext increased steadily for A and was stable for B. At critical points, both participants utilized rapid left shoulder internal rotation and adduction. Right shoulder motor behaviour strategies were markedly different between participants. For A, right shoulder rotation increased (showing internal rotation) and shoulder flex/ext decreased (showing extension) during P1 and P2 (green and orange lines, Figure 10D). As well, shoulder ab/add increased slightly (showing abduction) at critical points. During P3, motor behaviour in all three joints stabilized in narrow ranges. For B, right shoulder rotation decreased (external rotation) and ab/add increased (abduction), during P1 and P2 while there was a complementary exchange of roles between ab/add and rotation in P3 (green and blue lines, Figure 10C). Flex/ext usage appeared to be unperturbed throughout P1, P2 and P3.

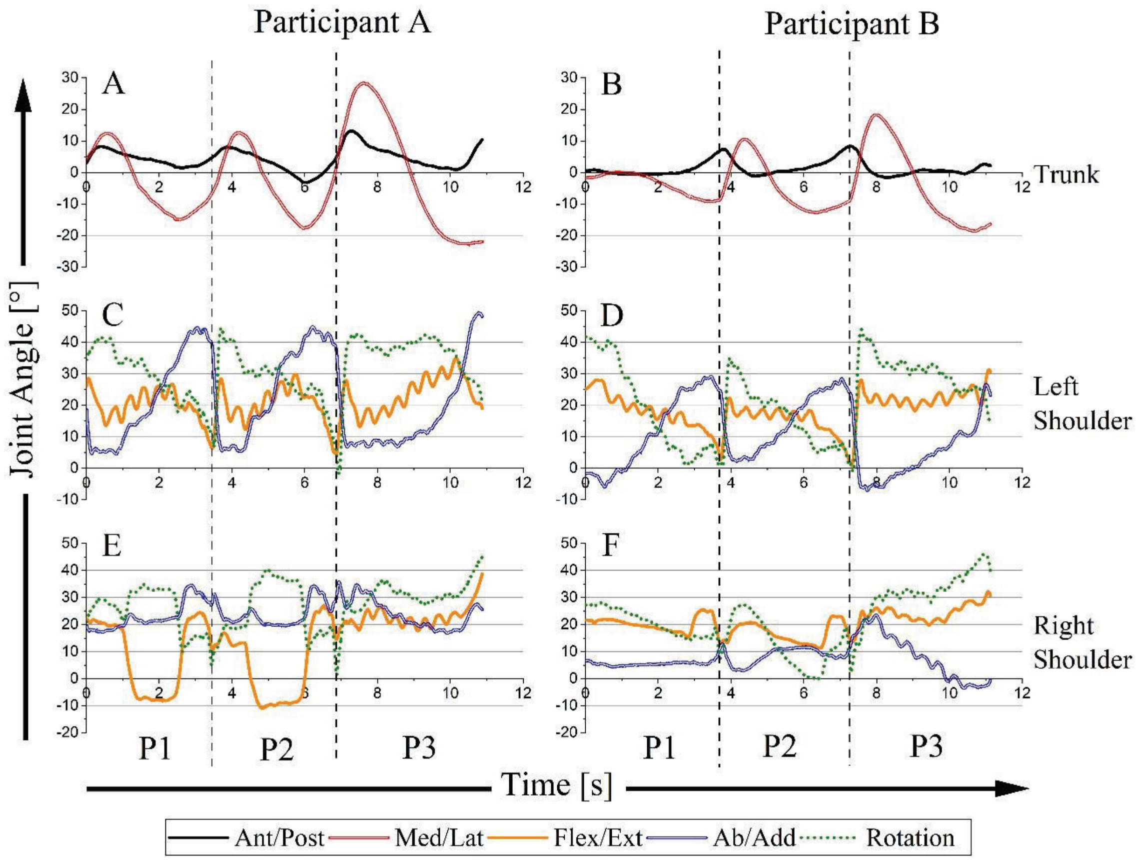


Figure 10: Trunk and Shoulder Joint Angles as a Function of Time for A and B. Note: Increased angles signify flexion (trunk and shoulders), lateral spinal flexion to the right (trunk), abduction, and internal rotation (shoulders). Zero-degree angles signify an upright spinal posture for the trunk and adducted, full external rotation of the glenohumeral joint.

Figure 11 shows joint angles for the elbows and wrists. For each performer, localized oscillations in the elbows and wrists were larger than those observed in the shoulders. For both performers, left elbow angles spiked suddenly (showing flexion) at critical points (red lines, Figure 11A and B). However, during each of P1, P2, and P3, participants' motor behaviours were opposite; A's left elbow angle decreased (showing extension) during each of these segments, while B's increased (showing flexion). Right elbow movement for A was much larger than for B (black lines, Figure 11A and B). For both participants, there was an anticipatory elbow movement leading to critical points; this strategy was more pronounced for A than for B. Right and left elbow joint movement was independently asymmetrical for A in P1 and P2. In P3, elbow movement became more symmetrical. For B, right and left elbow movement was more symmetrical throughout P1, P2, and P3. In the wrists, A used a right wrist flex/ext strategy throughout P1 and P2 (orange line, Figure 11C). In P3, A's wrist joint angles were stabilized. For B, flex/ext was consistently greater than rad/uln during P1, P2, and P3 (Figure 11D).

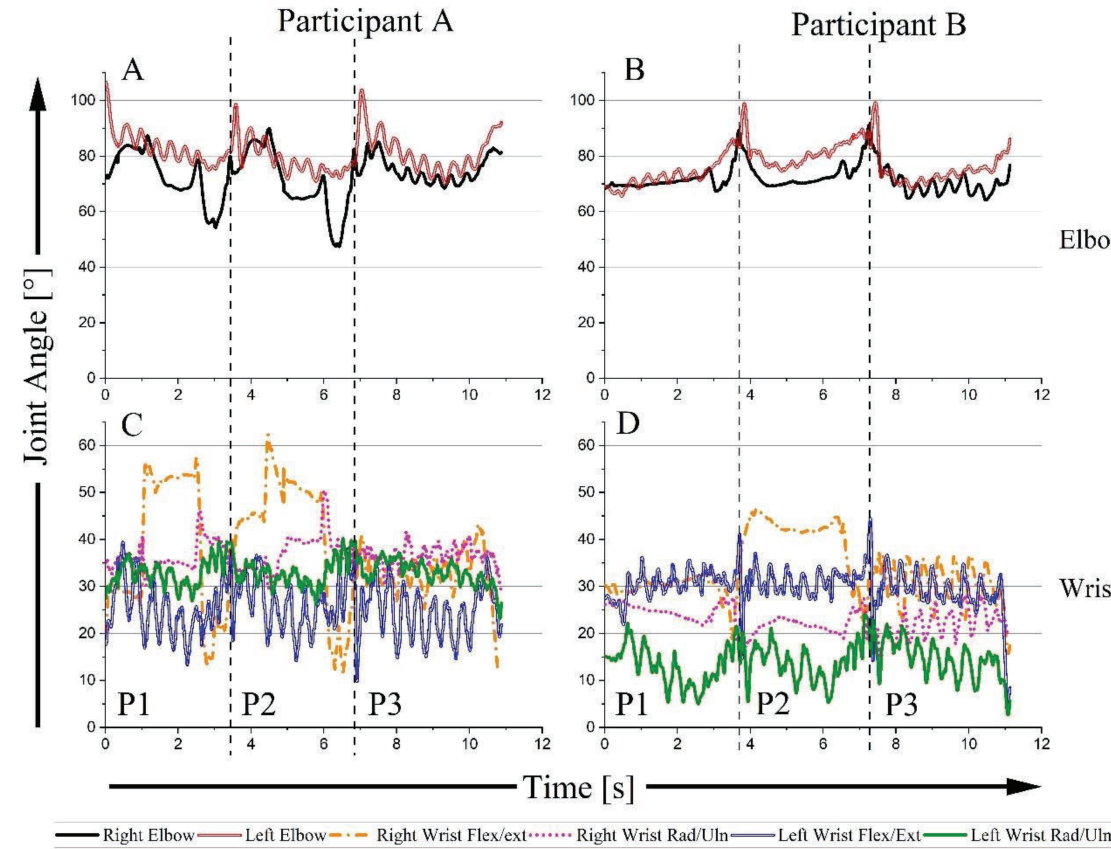


Figure 11: Elbow and Wrist Joint Angles as a Function of Time for A and B. Note: Increased elbow angles represent flexion while increased wrist angles represent flexion and ulnar deviation. Zero-degree joint angles represent full elbow extension and a neutral wrist position with no flex/ext or rad/uln deviation.

3.4 DISCUSSION

In the present study, we examined two expert pianists' gross motor behaviours while performing the complex opening of Chopin's Revolutionary Etude, and we analyzed the activity of the trunk, the joints of the shoulders (the glenohumeral joint), elbows, and wrists, and we quantified dynamic balance shifts in center of gravity (COG). We postulate that our use of elite pianists and a composition from the virtuosic literature led to performances that were influenced more by musico-cultural traditions and expectations than by experimental conditions. Performers' individual approaches were not constrained except by tempo and were apt to reflect their individualized artistic expression. Thus, the composer's musical directives, the performer's anthropometry, and the performers' motor strategies were all manifested in these data.

ROM data provided a general overview of each pianist's motor behaviour strategy. Given the detailed musical directives in the score of the Revolutionary Etude, it might seem that motor behaviour would be limited to a single possible strategy. Clearly, this was not the case, as each pianist used an individualized motor behaviour strategy. To understand how each pianist employed gross motor behaviour strategies in the service of a musical outcome, we analyzed: COG position, trunk movement, and shoulder, elbow, and wrist joint angles.

3.4.1 COG AND TRUNK

A adjusted the bench to be higher and closer to the keyboard compared to B. Starting COG positions for both pianists were indicative of their seating location; A was 0.7 cm anterior, 2.3 cm left, and 3.1 cm lower, compared to B's starting position. To some extent, bench position/height and starting COG positions may be explained by anthropometry. B was significantly taller than A, and positioning of the bench had to be further away from the piano for B's legs and arms to be in a comfortable orientation to the keyboard. However, anthropometry does not explain some of the motor control differences observed during the excerpt performance.

Within the music, P1 and P2 are nearly identical. A treated P1 and P2 with a consistent mechanical process, with shifts in both COG and trunk angles during P1 and P2 showing nearly identical contours (Figure 9A and C; Figure 10A). On the other hand, for B, COG and trunk angles showed markedly different mechanical processes during P1 and P2 (Figure 9B and D; Figure 10B), with B's COG and trunk angles looking more like those of A during P2. Clearly, the two participants used different starting approaches in their performances. A was more anticipatory in preparing the start than B, but by the time P2 occurred B had adapted his motor strategy to the demands of the composition. To some extent, anthropometry may have played a role. Since this composition required large lateral movements of the left arm across the body, A's shorter stature may have necessitated her anticipatory movement strategy. For B, a greater reach, because of his taller stature, might have made this less imperative. But, clearly by P2, B had modified his strategy to one that was more similar to that of A. Perhaps the difference between "viable" and "optimal" motor strategies explains this change.

At critical points, large physical movements needed to occur. At the first critical point, the left hand was required to move medial/laterally a distance of 48 cm, and at the second critical point it needed to move 65 cm. These movements occurred in less than 0.22 seconds. Shifts in COG can provide insight into motor strategies in this regard; differences between participants can be explained by both musical demands and anthropometry.

Both participants' COG shifted anteriorly, towards the keyboard, at critical points. Right and left hands were one octave apart, and bringing COG closer to the keyboard provided a means of leveraging body weight into the arms to assist the creation of a forte (loud) sound (spikes in graph contours of Figure 9A and B). Increases in med/lat COG excursions (trough to peak) at the second critical point may be partly explained by musical demands; the left hand needed to move one octave further on the keyboard. Notwithstanding musical constraints, anthropometry may help rationalize motor strategy differences between participants. A (the shorter pianist) utilized a preparatory strategy in anticipation of the large leaps at critical points (Figure 9C). There was no evidence of this for B, whose preparatory strategy did not require this adjustment, as he could reach further across the keyboard. Anthropometric differences may also explain the med/lat ROM disparity between participants (Table 2; A = 295 mm, B = 210 mm). A's larger COG movement may have been a compensation for a shorter reach.

Regardless of anthropometry, the trunk orients body position for all motor behaviours (Magill & Anderson, 2017). During piano performance, changes in trunk angle (COG position) has a concomitant effect on arm movement (Verdugo et al., 2020). Manipulation of trunk, shoulder, and elbow angles determines hand-keyboard orientation. Given that piano performance requires large changes in these variables as well as symmetrical and asymmetrical changes among these variables, trunk stability must be dynamic. This explains why, in the current study, participants' trunk angles changed in a gradual and controlled manner. The differences in control between participants may be explained by anthropometry. Particularly, for A, dynamic trunk stability employed a preparatory strategy. This preparatory strategy is biomechanically efficient because it takes less effort to move proximal body segments than distal ones (simply, there is less torque), and a preparatory strategy helps the performer achieve an earlier upper limb skeletal alignment, facilitating fine control of the fingers. Dynamic stability of the trunk influenced shoulder, elbow, and wrist motor behaviour strategies for both pianists. From a musician's standpoint, whether realized or not, gross motor movements must either be a response to (occurring after) or a preparation for (occurring before) musical demands. Strategy selection influences interpretive outcome.

3.4.2 SHOULDER

For both participants, left shoulder ab/add and rotation were complementary; abduction and external rotation were used in the movement strategy during P1 and P2. In general, there is no utility in moving the left shoulder in the flex/ext plane because the keyboard and bench height are fixed. A scenario in which significant manipulation of shoulder flex/ext might occur would be when an arm needs to accommodate trunk position (e.g., it must move in front of the trunk, resulting in shoulder flexion). A's use of a preparatory trunk movement strategy can be observed in flex/ext of the shoulder (Figure 10C, orange line). Whereas her shorter stature generally required flex/ext to increase (flex) for the descending left-hand musical patterns, anticipatory trunk movement permitted her to reduce flexion at the ends of P1 and P2. For B, left shoulder flex/ext decreased throughout each P1 and P2 because there was no preparatory trunk movement; flex/ext increased suddenly in coordination with the large left-hand leaps.

For the left shoulder both participants utilized rapid internal rotation and adduction to accommodate large left-hand leaps at critical points. This strategy takes advantage of the low inertial properties of shoulder rotation, enabling fast and easy arm movement across the keyboard without negatively affecting "smoothness" of arm control in the distal segments. We suspect that both participants utilized the same strategy because of timing constraints. Since movement at the critical points needed to occur in less than 110 ms, using internal rotation and adduction of the left shoulder made the passage possible. Any strategy that involved larger movement of distal segments would have taken more physical effort (given a non-infinite availability of physical force, more effort means more time).

For the right shoulder, each pianist used different motor strategies. This was a product of the manner in which they chose to utilize musical rests (when no notes are being played) during P1 and P2. Right hand behaviour during P1 and P2 can be divided into three distinctive sections: (a) musical rests, (b) a “pickup”, or gesture leading into, (c) a chord. A used right shoulder extension and internal rotation during the musical rests (“active rest”) as a mechanism to prepare for the leading gesture, whereas B used right shoulder external rotation and abduction. A used the rests as opportunities to “relax” the right limb, choreographing its re-entry into the musical context just before it was needed. For A the right and left limbs operated independently. B maintained playing preparedness in the right limb throughout the rests. In this manner, the right and left limbs operated more dependently. Both of these choreographic strategies have utility. Certainly, for short periods of rest, an active hand choreography should facilitate musical fluency. For longer periods of rest, especially for a composition of some significant length, utilizing musical rests as opportunities to relax muscle groups may delay fatigue and reduce its concomitant and negative impact on musical precision and outcomes. The excerpt used in the current protocol was short, and the right limb rests lent themselves to either option. Of course, choice of strategy in this regard necessitates differences in COG shifts.

For A, the act of putting her right hand on her right thigh during musical rests was a means to rest the right shoulder and arm muscles. For B, choreographing the right arm in and out of the musical gesture proved to be a joint activity minimization strategy for both limbs. By resting the right limb, temporarily removing it from the musical gesture, all effort was focused on left-limb execution, permitting small joint movements with a concomitantly larger COG shift in the trunk. When only considering the moments where the right limb was active (not resting on the thigh), all joint angles exhibited narrow ROM, showing considerable motor efficiency. For B, maintaining right arm activity throughout the rests allowed him to reduce right arm joint movement in a different manner. For B, there was no need for a timing choreography to reintroduce the right arm into the musical gesture. His larger reach permitted this as well as smaller COG movement.

3.4.3 ELBOW

At critical points, both participants flexed (increased joint angle) the left elbow to accommodate for large leaps in the music. During all P1, P2, and P3, A used extension of the left elbow (decreased joint angle) to guide the left hand as it descended the keyboard. Greater COG ROM facilitated this. B utilized elbow flexion as his arm “reached” down the keyboard. Greater reach permitted smaller COG ROM.

Right elbow movement was different between participants because of the manners in which they used musical rests. For A, the right elbow was flexed during the rest period and extended during the “pickup” gesture in preparation for the chords. For B, right elbow angles mimicked those of the left elbow. This strategy reduced the complexity of limb movement in a passage of music that demanded asymmetrical arm movements.

3.4.4 WRIST

Dynamic stability is observed through the oscillations in wrist joint angles – more distal joints (i.e., the wrists) exhibited greater oscillatory patterns compared to more proximal structures (i.e., the shoulders). For every accent in the excerpt there was an oscillation in the wrist to generate a louder/stressed sound. In terms of motor behaviour, the accents “chunked” the fast notes into groups of four.

A used right wrist flexion to prepare right-hand chords at each critical point during the musical rest section. During P3, wrist joint angles were stabilized because the trunk was positioned between both hands, resulting in no need to excessively flex or deviate the wrist. For B, a larger hand size may have meant that flex/ext had greater utility than rad/uln because of increased “reach”.

3.4.5 LIMITATIONS AND FUTURE DIRECTIONS

The current study suggests that there are many successful strategies available to pianists to accomplish any given performance outcome. It may be that some strategies are more useful to some pianists, given anthropometric variability. The current study provides a framework for future research intending to analyze and train motor behaviours during piano performance. Ultimately, with a large enough body of evidence, such work can demystify complex motor behaviour and strategizing during pedagogy and performance. Since this study analyzed the movements of only two elite pianists, it can only be considered a proof of principle, providing a starting point for future research that might possibly include the examination of additional anthropometric measures (e.g., hand span and finger lengths). Further, the current analysis only involved a small portion of a single composition. Finally, we made no attempt in this study to determine optimal performance movements or optimal training strategies for such complex activities. We assumed that these elite performers would provide a model against which further pedagogical research might compare the performances of students with similar anthropometry.

3.5 CONCLUSION

In the current case comparison, both pianists displayed compensatory movements suitable for their own anthropometry and interpretations of musical demands. For both performers, shifts in COG and trunk position had considerable influence on the distal segments of the upper limbs. These shifts were used to enable rapid lateral hand movement. The shorter pianist used larger shifts in COG and trunk position than the taller one. This enabled her to foster a dynamic stability, effectively compensating for a smaller stature. This performer's motor strategization was remarkably consistent throughout the excerpt, and anticipatory of the discontinuous melodic demands at critical points in the music (points where abrupt gross movement was required). Notably, A, used a COG shift even prior to her playing the first note of the composition, emphasizing that this strategy was preparatory rather than reactive. The effect of the above strategy was augmented by left shoulder movement, where rapid internal rotation and adduction was used to minimize the effort of playing the large left-hand leaps. This strategy takes advantage of the low inertial properties of shoulder rotation, which enables fast and easy arm movement across the keyboard. For the right arm, motor strategization was confounded by the presence of rests in the music; two performative possibilities existed: (a) to use the rest as an opportunity to temporarily relax muscle groups in the right arm, or (b) to maintain a directed right arm choreography throughout the rest. The two pianists of the current study chose different strategies and, correspondingly, motor control of the right-shoulder joints was very different. A used the opportunity to relax the arm, while B maintained a directed tension throughout the rests. No attempt was made to evaluate whether one of these strategies was "better" than the other however, in longer performances, the first strategy might better assist in fatigue management. With regard to the left and right wrists, the performer with the smaller hand size (A) used more rad/uln deviation while the performer with the larger hand size (B) used more flex/ext.

These results, as an initial investigation, might suggest that the personal 'style' and individual creativity of a performer can be derived from their development of a variety of motor behaviours that are compensatory in nature; accommodating body size and shape and motivated by outcomes that show individualized respect for the musical context. Thus, incorporating scientifically based motor learning strategies into complex piano pedagogy should help accelerate cognitive and perceptual motor skill acquisition and expand the range of motor behaviours available for student musicians seeking to manipulate motor movements in the service of artistic interpretation. Introducing this approach early in pedagogy may help learners avoid the acquisition of unnecessary muscular tensions and idiosyncratically inefficient motor behaviours

We propose that elite pianists' personalized motor behaviours are compensatory in nature; they adapt to affect the musical desires of the performer and are partially constrained by anthropometry. From a practical standpoint, analyses of motor behaviours will be most meaningful if they are sensitive to both a performer's musical intentionality and his/her potential for motor strategization, developed over decades of practice. In the athletic endeavour that is music performance, augmenting knowledge of motor strategies has the potential to positively influence music teaching and learning and expand movement science methodologies, broadening the scope of both music and movement science disciplines.

CHAPTER 4: A CASE COMPARISON OF THREE PIANISTS: EXAMINING TRUNK AND RIGHT-HAND COORDINATION IN PIANO PERFORMANCE

4.1 INTRODUCTION

Attaining an advanced level of piano performance skills requires years of training. It is estimated that 17 million people worldwide play the piano at an advanced level (Harris, 2017). In western pedagogical traditions, music learning occurs in a one-on-one student-teacher setting. Typically, students receive only one instructional session per week; the majority of time spent learning involves individually motivated practice. For piano students enrolled at university, weekly practice hours can be as high as 39 hours per week (Kaufman-Cohen et al., 2019). For professional pianists, average practice hours can range from 3.3-3.83 hours per day (Moñino et al., 2017; Jabusch et al., 2009) or 13.7-27 hours per week (Allsop & Ackland, 2010; Ericsson et al., 1993; Krampe & Ericsson, 1996). Clearly, given the long hours of necessary self-directed practice, the learner must be equipped with both cognitive and motor-based learning strategies that are grounded in deliberate and directed practice.

Motor learning research has shown that engaging in deliberate practice improves skill acquisition (Baker et al., 2020). With regard to the biomechanics of music performance and the ergonomics of interacting with a piano, deliberate practice can be a challenge because, a) most music teachers are not trained in the fundamentals of movement science, and b) the majority of music biomechanics pedagogy is based in empirical methodologies – the subjective experience of the teacher (Shan et al., 2013; Visentin et al., 2008). Since there is a strong reliance on teachers' abilities to communicate personal perceptions of their own experiences, this model of pedagogy has limitations (Turner et al., 2021a); learning tends to involve a significant amount of trial-and-error practice. This can result in the acquisition of "bad practice habits" or the development of idiosyncratic playing styles, which has implications for increased risk of playing-related injuries. To better optimize learning, students of piano need to be provided with motor learning strategies that are grounded in biomechanics and ergonomics. Unfortunately, in existing research, there is sparse discussion of meaningful motor learning strategies devoted to optimizing piano performance (Turner et al., 2021a).

In piano performance, a performer is required to physically move. A piano keyboard has 88 keys that are fixed in location and span a distance of 1.22 m. Since the keyboard is stationary, performers must adjust their position to the piano, coordinating trunk and upper limb movement according to the demands of the musical score. For high-level performers, movement becomes autonomous, but may be subject to conscious manipulation in the pursuit of musical goals. From a biomechanical standpoint, utilization of the trunk during coordinated movement provides a more efficient means of executing motor skills (Turner et al., 2021a). In sports, the use of proximal musculature to facilitate distal movement is well documented (Shan & Westerhoff, 2005; Zhang & Shan, 2014; Zhang et al., 2016). In music, proximal-to-distal movement sequencing has been examined for drumming (Altenmüller et al., 2020) and piano keystrokes involving a "struck touch" (Furuya & Kinoshita, 2007; Verdugo et al., 2020). Pappa et al. (2020) reported that adolescent novice pianists exhibited more trunk and hand movement while playing scales at fast tempos compared to more experienced adolescent pianists. Turner et al. (2021a) analyzed the timing of shifts in balance during performance of a virtuosic piano composition. Since music performance is a temporal art, movement coordination is dependent on timely preparation; when and how a pianist prepares for movement greatly affects performance. A directed awareness of the role that proximal body segments play in preparation for and initiation of limb movements can be a means of optimizing performance strategies and improving musical outcomes.

Optimizing performance strategies requires consideration of a pianist's anthropometry and skill level in terms of the musical demands of the composition being performed. Anthropometrical characteristics dictate how a motor skill is learned (Ballreich, 1996). Because anthropometry differs among individuals, this suggests that most motor learning must be individualized. In music performance, motor behaviour can vary greatly depending on the music being performed and the skill level of the performer. Advanced performers strategize and manipulate gross and fine motor skills in order to achieve artistic and interpretive musical outcomes (Shan et al., 2013). Mere repeatability is not the goal. This complexity makes the study of music performance and the application of motor learning methodologies very challenging.

In the current case study, two expert pianists and one intermediate pianist performed the last 9 measures (mm. 363 to 371) from the 3rd movement of Beethoven's Sonata in F Minor Op. 57 ("Appassionata") at three different playing speeds. Preparatory movements involving timely coordination of the trunk and right hand (RH) were analyzed. The purpose of the current study was to begin discussion of piano performance with regard to trunk and RH coordination, movement-based preparation strategies, anthropometry, skill level of the performer and, musical context.

4.2 METHODS

4.2.1 PARTICIPANTS

Three pianists (two males and one female) of differing anthropometric characteristics and skill levels were recruited for the study (Table 3). Participants 1 (P1) and 2 (P2) were professionals with completed Doctorate degrees. Participant 3 (P3) was an intermediate level pianist with 11 years of piano study. All participants were right-hand dominant and, according to the Beighton Hypermobility protocol, exhibited no signs of hypermobility. Participants gave written informed consent after a briefing on the research protocol and procedures, all of which were approved by the University of Lethbridge Human Subject Research Committee [approval #2018-098].

Table 3: Sex, select anthropometric measures, handedness, and experience level of each participant in the study.

Participant	Sex	Body Height (m)	Hand Span (m)	Hand Length (m)	Forearm Length (m)	Upper arm length (m)	Handedness	Experience Level
P1	Female	1.645	0.178	0.172	0.253	0.289	Right	Expert
P2	Male	1.900	0.203	0.219	0.270	0.331	Right	Expert
P3	Male	1.735	0.193	0.192	0.258	0.326	Right	Intermediate

4.2.2 MUSICAL EXCERPT

Participants performed the last 9 measures (mm. 363 to 371) from the 3rd movement of Beethoven’s Sonata in F Minor Op. 57 (“Appassionata”) (Figure 12), an excerpt exemplary of the virtuosic literature from the early Romantic period. Three playing speeds were examined: 6, 8, and 10 notes/second (N/s). Performing at the fastest tempo (10 N/s) is an expert task. To do so with artistic motivation requires years of training. Participants were instructed to perform in accordance with Beethoven's instructions in the score but without using the pedals. Excluding the pedals permitted focus on upper body movement without the confounding variable of right-foot pedaling. Participants had the music available to them during data collection however, based on visual observation, none were reading from the score when performing.

The musical excerpt divides into three sections (A, B, and C) based on distinct motor demands for the RH: A) a gradual, descending series of "broken" 4-note chords covering a lateral to medial distance of 57cm (3.5 octaves), B) a medial-to-lateral jump using "blocked" chords and covering a distance of 32.5cm (2 octaves), and C) a lateral-to-medial jump using "blocked" chords and covering a distance of 16.25cm (1 octave). Throughout the excerpt, the LH was stable in terms of medial/lateral position, playing a repetitive 4-note pattern for the first six measures, and the same four notes in "blocked" chords for the last three measures. These kinds of motor behaviour demands are common in western musical tradition. Many pedagogical sources, such as "Essential Finger Exercises for Obtaining a Sure Piano Technique" by Ernő Dohnányi (1929), deliberately cultivate medial-lateral motor behaviours using chordal patterns.

Figure 12: The last 9 measures (mm. 363 to 371) from the 3rd movement of Beethoven's Sonata in F Minor Op. 57 ("Appassionata") with three identified motor behaviour phases: gradual RH descent (Section A), 2-octave medial-to-lateral RH jump (Section B), and 1 octave lateral-to-medial RH jump (Section C).

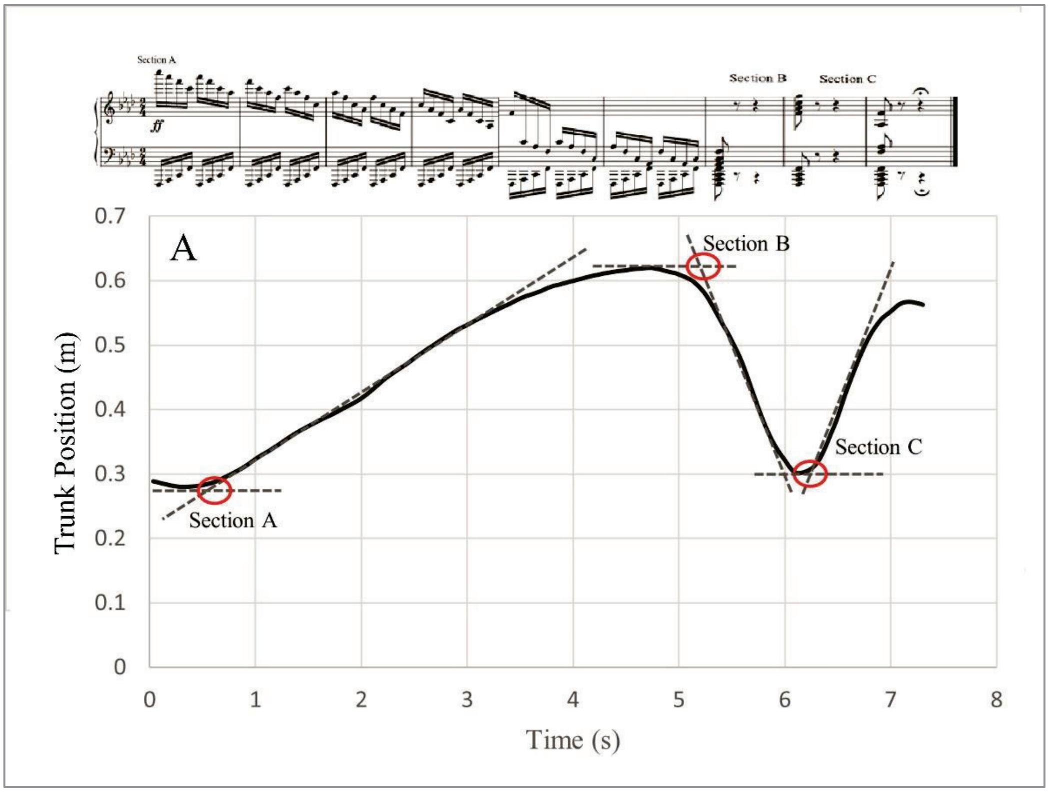
4.2.3 DATA COLLECTION PROCEDURE AND ANALYSIS

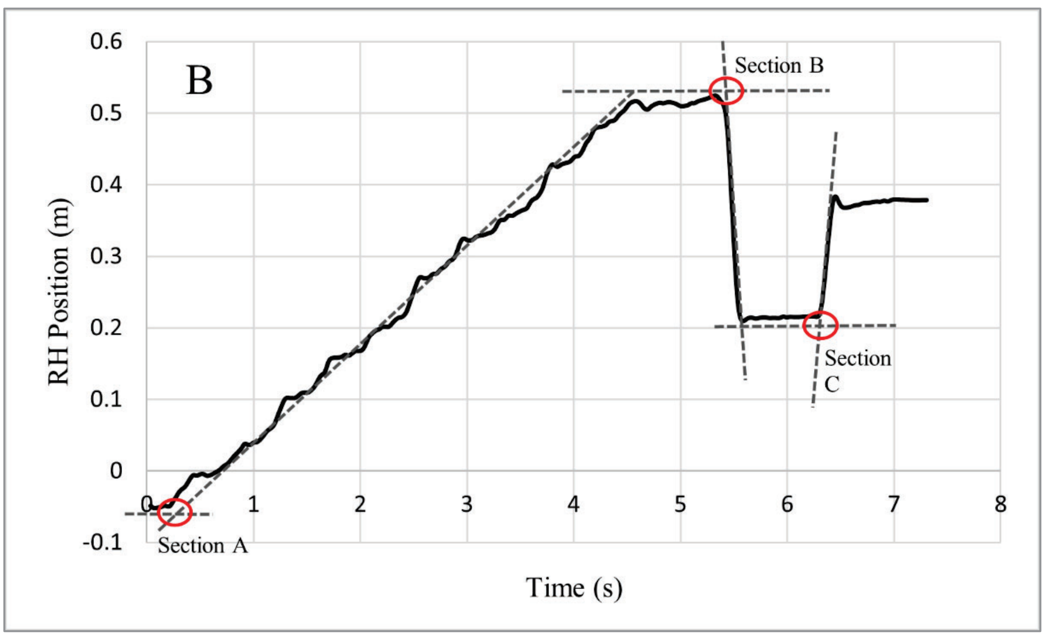
To quantify movement during performance, reflective markers were placed on six key anatomical landmarks and a ten-camera motion capture system (VICON MX40, Oxford, England) recorded positional and kinematic data. Capture frequency was 200Hz (calibration error <0.6 mm). One marker was placed on C7 and five were placed on the distal phalanges of the RH. The C7 marker provided a reference for trunk position while the RH position was determined using the five markers on the RH. 88 markers were placed on the keys of the piano to identify keystroke timing and accuracy.

To simulate a realistic performance setting, participants performed on a 9-foot New York Steinway grand piano in a concert hall (Figure 13). Each pianist was permitted to adjust the piano bench height and position according to personal preference. During data collection, tempo (playing speed) was regulated using a metronome.

Figure 13: The experimental set-up of the motion capture system in the concert hall.

To establish timing of motor control, medial/lateral movement for the RH and trunk was analyzed using a global center point for the RH and the C7 marker. The positional data of the five RH markers were averaged to determine a global center point for the RH. RH position is plotted in figure 14a. Medial/lateral movement of the trunk (C7) is plotted in figure 14b. "Best fit" slopes for each of the graphs were determined using linear regression (dotted lines – Figures 14a and 14b). The intersection of these slopes establishes time-points where changes in motor control occur. Control changes coinciding with the beginnings of A, B, and C are identified using red circles (Figures 14a and 14b). Initiation intervals were defined as the difference in time between trunk and RH time-points. Positive values indicate that the trunk starts moving before the RH and negative values indicate the converse. Since the selected excerpt employs a static LH position, only the RH was analyzed.





Figures 14a and 14b: An example of the method used to calculate initiation time points. The intersection points between the initial position and positional slope (red circles) indicate the initiation time for the trunk and RH in each section of the musical excerpt.

4.3 RESULTS

Medial-lateral starting position of the trunk differed among participants. The two expert performers began with a C7 starting position that favoured the RH. For P1, C7 was, on average, 65.9mm closer to the RH than to the LH and for P2, this distance was 33.9mm. For the intermediate performer, C7 starting position favoured the LH by 7.2mm.

Initiation intervals for each participant are shown in Table 4. During the first section of music (A), interval values are negative, indicating that all participants initiated with the RH. As tempo increased, initiation times for P1 decreased while, for P2 and P3, initiation times increased from 6N/s to 8N/s and decreased at 10N/s (Table 4). Average initiation times were distinctly different for each subject, -0.450s, -0.927s, and -0.668s for P1, P2, and P3, respectively. During section B, trunk movement preceded RH movement. For the expert pianists, P1's initiation intervals were remarkably consistent across all tempos (0.205s, 0.215s, 0.185s) while P2's were more variable (0.350s, 0.490s, 0.260s). For P3, the intermediate-level pianist, initiation intervals steadily decreased as tempo increased (0.355s, 0.210s, 0.050s). During section C, P1's initiation intervals were consistently close to zero (-0.050s, 0.015s, -0.005s), with an average of -0.013s across all tempos. For P2 and P3, initiation intervals decreased as tempo increased, (0.695s, 0.220s, -0.155s) and (0.445s, 0.155s, 0.195s) for P2 and P3, respectively.

Table 4: The initiation intervals between the trunk and RH for all three sections of the music across the three tempos. Trunk initiations are in bold print.

Participants	Tempo (N/s)	Music Sections					
		A (s)	Average of A (s)	B (s)	Average of B (s)	C (s)	Average of C (s)
	6	-0.885		**0.205**		-0.050	
P1	8	-0.330	-0.450±0.385	**0.215**	0.202±0.015	0.015	-0.013±0.033
	10	-0.145		**0.185**		-0.005	
	6	-1.080		**0.350**		**0.695**	
P2	8	-1.355	-0.927±0.522	**0.490**	0.367±0.116	**0.220**	0.253±0.426
	10	-0.345		**0.260**		-0.155	
	6	-0.465		**0.355**		**0.445**	
P3	8	-0.800	-0.668±0.179	**0.210**	0.205±0.153	**0.155**	0.265±0.157
	10	-0.740		0.050		**0.195**	

Trunk ROM across all tempos are shown in table 5. For each musical section (A, B, and C), P1 had the largest trunk ROM, P2 had the smallest trunk ROM, and P3's ROM was somewhere in between. Across musical sections A, B, and C, each of the participants had highest trunk ROM in section A and lowest in section C, with section B ROM falling in between. Looking at the extreme speeds, slowest and fastest tempos only: in section A, ROM for P2 increased while it decreased for P1 and P3; in section B; ROM increased for P1 and P2 while it decreased for P3; and, in section C, ROM increased for P1 while it decreased for P2 and P3.

Table 5: Trunk ROM (mm) across all tempos and sections of the musical excerpt.

	Trunk Range of Motion (mm)											
	Section A				Section B				Section C			
Participants	6N/s	8 N/s	10 N/s	Average	6N/s	8 N/s	10 N/s	Average	6N/s	8 N/s	10 N/s	Average
P1	313.3	340.0	272.2	308.5	262.1	318.5	270.1	283.6	191.0	265.6	254.2	237.0
P2	147.4	155.7	198.8	167.3	76.3	80.4	94.8	83.8	66.2	55.8	32.3	51.4
P3	188.0	167.7	174.0	176.6	164.5	135.5	107.3	135.8	83.8	89.0	27.3	66.7

In figure 15, medial-lateral RH velocity of the two expert pianists (P1 and P2) showed similar motor behaviours while the intermediate performer (P3) had a markedly different motor behaviour. Maximum RH velocities achieved by P1 and P2 were 1.6 m/s and 1.4 m/s. For P3, maximum RH velocity was 0.8m/s. Velocity curve contours showed similar differences. For P1 and P2, velocity curve contours were smooth and continuous with medial-lateral movement completion requiring ~0.22s while, for P3, the curve contour was irregular and movement completion required more than 0.5s.

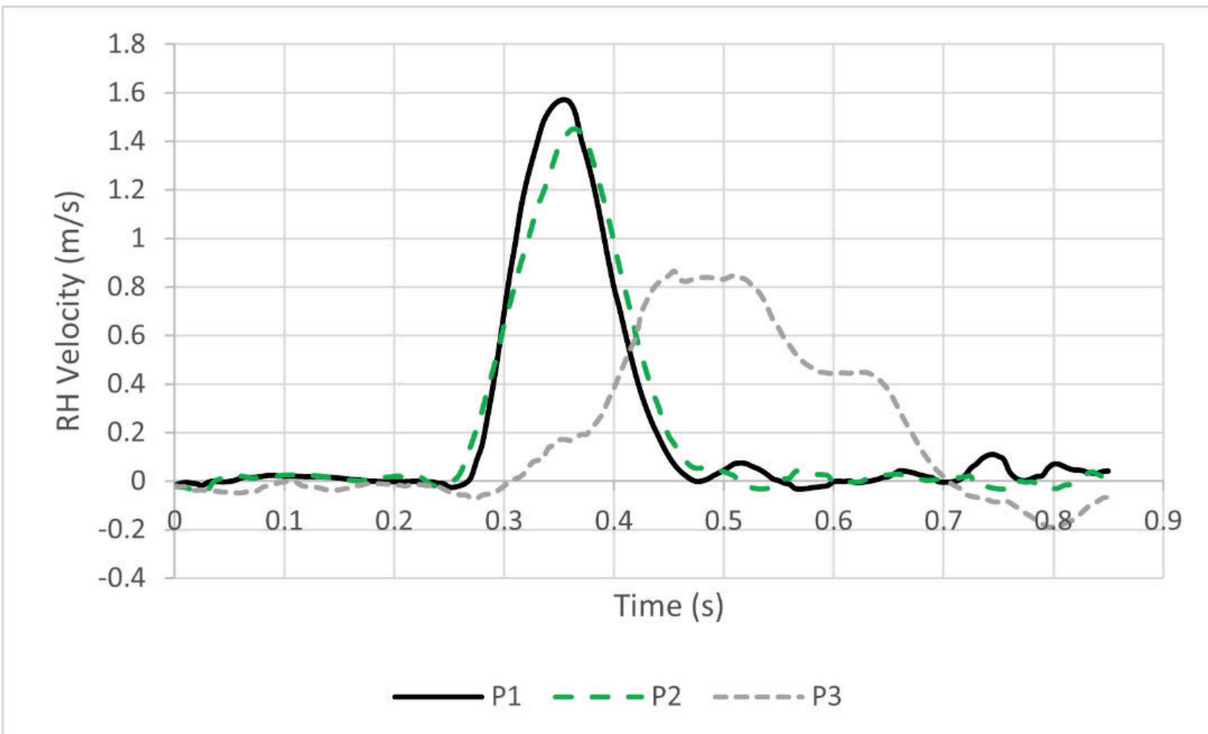


Figure 15: RH velocity for all pianists during section C at 10 N/s.

4.4 DISCUSSION

In compositions such as Beethoven's Appassionata Sonata, both proximal (trunk) and distal (hands) body structures must move; the distances between the notes are simply too big for the trunk to be static, and the music effective. When coordinating body segments for complex movements, relevant questions are “what moves first?” and “why does it do so?”. The current study answers these questions by examining musical demands, initiation intervals, ranges of motion in the trunk and the hands, expertise levels, and anthropometry for each of sections A, B, and C of the selected musical excerpt.

4.4.1 STARTING POSITION

Whether consciously rationalized or not, a pianist’s starting position is the first preparatory decision they must make. Position influences the availability of movement options for the performer, and consequently can be considered in terms of both expertise and anthropometry (Ackermann & Adams, 2003; James, 2018; Vantorre et al., 2014). In the current study, medial-lateral motor demands placed on the RH were considerably greater than those for the LH. Expert performers positioned themselves closer to the RH than the LH, effectively adjusting skeletal alignment to provide better proximal support for the RH. In contrast, the intermediate performer’s starting position, equidistant between his hands, fails to recognize the demands imposed upon the RH. This finding is likely evidence of a skill level differential. The two expert players, because of long-term training, “naturally” positioned themselves asymmetrically to favour the hand executing the more difficult passagework.

In addition to expertise, anthropometry underpins data regarding starting position. P1, the shortest performer, started 65.9mm closer to the RH than to the LH. For P2, the tallest performer, this positional asymmetry was only 33.9mm. Simply, P1’s shorter reach required greater compensation from the trunk as a means of supporting fine motor execution in the RH. For P3, given his stature, it seems reasonable to expect that playing optimization would have required him to position his trunk somewhere between 33.9mm and 65.9mm closer to the RH. A learning environment sensitive to biomechanics and the influence of anthropometry could help such a performer improve ease of playing and performance outcomes.

4.4.2 INITIATION INTERVALS

Section A of the music has continuous playing involving movement throughout the right limb. Since the right limb must begin in an extended position, the consistent initiation of movement with the RH by all participants can be understood from a standpoint of effort minimization. The RH has a greater medial-lateral mobility than the trunk and, since it has less inertia, it is the easier segment to move. This underpins the role of the RH as the initiator of movement in section A of the excerpt. Average initiation intervals were smallest, largest, and in-between for P1, P2, and P3, respectively (Table 4). The small initiation interval for P1 indicates that she is moving the trunk more closely in tandem with the RH. In using this strategy, proximal-to-distal skeletal support is better maintained throughout the entire passage. For P2, longer upper limbs permitted a greater medial-lateral right arm reach and a correspondingly smaller reliance on trunk movement. His larger initiation interval, nearly double that of P1, indicate that he was less dependent on moving the trunk to optimize skeletal alignment in support of the RH. For P3, initiation times fell in between that of P1 and P2 suggesting his stature, intermediate to P1 and P2, to be a determining factor.

In music section B, the presence of “rests” in the music influences the motor strategization. During rests, a pianist does not play any notes, so the body has greater behavioural freedom in preparation for upcoming playing demands. In spite of this increased freedom, in section B, all participants initiated movement from the trunk. This supports the idea expressed by Furuya & Altenmüller (2013) that proximal-to-distal motor coordination might help optimize motor behaviour. In section B, other musical demands also affect movement; a *fortissimo* ("very loud") "blocked" chord occurred after the RH medial-to-lateral jump of 32.5cm (two octaves), making trunk movement necessary to support the RH. This substantiates the findings of Verdugo et al., (2020) with regard to the involvement of the trunk during *forte* ("loud") playing. For P1, initiation intervals across all tempos were remarkably consistent (Table 4), with less than 3/100^{ths} of a second difference between trials. This consistency suggests P1's expertise to be very high. For P2 and P3, initiation intervals varied somewhat more than for P1 (0.23s and 0.305s for P2 and P3, respectively). This variance is still small, showing high levels of expertise.

Section C of the music ends the composition and requires a "very loud" finishing gesture. P1's use of simultaneous trunk and RH movement (initiation intervals across all tempos varied less than 0.065s), show her to be maximizing trunk support to achieve this effect. For P2 and P3, the RH became more closely synchronized with the trunk at the two faster tempos. This shows P2 and P3 to be optimizing trunk support for the RH as the difficulty of playing increased.

4.4.3 TRUNK ROM

At all tempos, average trunk ROM was largest, smallest, and in-between for P1, P2, and P3, the tallest-, shortest-, and medium-sized pianists, respectively (Table 5). This suggests anthropometry to be an important factor for trunk movement. For P1, the participant with the shortest arm reach, a larger trunk ROM may have served as a compensatory mechanism to optimize RH support. P2's longer upper limbs permitted a greater medial-lateral arm reach and greater leverage when striking the piano keys, so less trunk movement was required in general. For P3, trunk ROM was intermediate to those of P1 and P2, a finding consistent with his physical stature. Comparing sections of music, each participant's average trunk ROM was greatest in A, less in B, and least in C. This phenomena appears to be coupled with RH playing demands; the RH moves furthest in A, less in B, and least in C.

Tempo-dependent trunk ROM is revealing with regard to movement strategization. P1 used much more trunk ROM than either P2 or P3. For P1, reducing proximal movement trunk ROM had utility as an efficiency measure. At faster tempos, since there was less time to move, P1 reduced trunk movement (Table 5). For P2 and P3, because they were moving so much less than P1 overall, there was little efficiency gain to be had by employing P1's motor strategy.

4.4.4 RIGHT LIMB COORDINATION

Analyzing RH coordination provides insight on expertise. The complex RH movement patterns of P3 are in stark contrast to those of P1 and P2. This can be clearly seen in figure 15, which compares RH velocities of all participants for section C of the music at 10N/s. P3 moves in "fits and starts" while P1 and P2 have smooth and continuous RH velocity changes. For P3, trunk movement is nearly frozen in this trial, moving only 27.3mm, which is evidence of his lesser expertise; his RH must attempt to compensate for reduced trunk movement. In the context of piano performance, movement strategies must be sublimated into artistic intention, and these are expertise dependent. A further consequence of suboptimal movement behaviours is that they have the potential to increase risk of playing-related injury (Taimela et al., 1990; Turner et al., 2021b). In the case of P3, pedagogical instruction directing his attention towards trunk movement may have improved his coordination.

4.4.5 LIMITATIONS AND FUTURE WORK

The current study asserts that anthropometry, skill-level, and musical context are all necessary considerations when learning to perform the piano. As a case comparison, it only involves three participants, two experts and one intermediate-level participant. As such, the utility of the current study lies in the data supported hypotheses rationalized in the discussion. Since piano performance involves an array of musical contexts, more studies are needed to come to a complete understanding of how musical context directs motor strategization; a larger body of work examining practical biomechanical strategies is needed. Lastly, the current study made assumption that the performers were not deliberately manipulating their "natural" playing style. A parallel line of research should be developed looking at cause and effect of the conscious manipulation of movement strategies in the service of artistic performance.

4.5 CONCLUSION

In the current case study, three pianists' timely coordination of the trunk and right hand (RH) preparatory movements were analyzed during performance of the last 9 measures of Beethoven's "Appassionata" Sonata, at three different playing speeds. The musical excerpt had three different sections requiring distinct motor behaviours for the RH, while the LH remained relatively stable. This permitted examination of preparatory strategies for each of the various motor behaviours. Starting position, initiation intervals, trunk ROM, and right limb coordination were analyzed. All of the findings underpin consideration of expertise and the influence of anthropometry on piano performance.

Experience-levels of the performers became clear when examining starting postures/positions. In section A of the music, the starting trunk positions of P1 and P2, the expert performers, were closer to the RH in anticipation of the excerpt's medial-lateral, right limb extension demands. This shows evidence of long-term training and high-level expertise. P3, the intermediate-level performer, neglected to anticipate musical demands and positioned his trunk equidistantly between the LH and RH. Starting position was equally elucidating regarding anthropometry; even though both expert performers employed asymmetrical trunk positions, the shorter performer employed significantly more than the taller performer. This provided her mechanical compensation for a shorter arm reach. Average initiation intervals during section A revealed that all participants initiated their movement with their RH, the trunk following. Initiation intervals during section A were largest, smallest, and in-between for P1, P2, and P3, the tallest-, shortest-, and medium-sized pianists, respectively. This suggests anthropometry to be a factor in terms of timely coordination. In sections B and C, the presence of musical "rests" permitted more behavioural freedom in terms of timely coordination. Remarkably, all participants initiated their movement using proximal-to-distal coordination (trunk first and RH following). For P1, trunk and RH coordination in section C becomes effectively synchronized in order to achieve a *fortissimo* finishing gesture. This was true at all three playing speeds. Anthropometry also appears to be important with regard to trunk ROM; average trunk ROM was largest, smallest, and in-between for P1, P2, and P3, the tallest-, shortest-, and medium-sized pianists, respectively. Tempo-dependent trunk ROM is revealing with regard movement strategization. The generally larger trunk ROM employed by P1, the smallest performer, permitted her to reduce proximal movement (ROM) as an efficiency measure at the fastest playing speed. P2 and P3 had little efficiency to be gained by using this strategy. Examination of RH velocity is revealing with regard to player expertise. The expert performers manipulation of velocity was smooth and continuous, whereas the intermediate-level performer's use of velocity was irregular.

The current study underpins the utility of recognizing the influence of biomechanics, anthropometry, skill level and motor learning strategies in piano learning and performance. Comparative analyses such as those of the current study provide biomechanical and ergonomic perspectives that have potential to optimize the process of learning to play the piano. Individualization of preparatory strategies should be recognized in terms of the anthropometry of the learner. The generally accepted concept that proximal body structures initiate movement may not be possible depending on musical context. In this case, expertise and anthropometry need to be considered more carefully. Future studies of this concept could contribute to more effective motor learning. In addition to improving musical outcomes, this has the potential to optimize movement intentionality in the service of injury prevention.

CHAPTER 5: THESIS CONCLUSION

In the current thesis, I postulate that providing pianists with motor learning strategies that are respective of individualized factors related to biomechanics of human movement, anthropometry, and musical context, can help optimize performance outcomes while simultaneously reducing the risk of playing-related injury. Through its three case comparison studies, the current thesis provides model frameworks for future research. These studies address both kinematics and kinetics since, in terms of motor learning, kinematics has significant utility in terms of improving teaching and learning while an understanding of kinetics is essential for reducing risk of playing-related injury. Both kinematics and kinetics have significant utility in raising a performer's awareness of biomechanical "cause and effect", thus giving them additional tools to optimize their musical intentions.

Clearly, musicians' artful manipulation of motor behaviours to effect musical intentionality makes this a complex process. Thus, the current thesis exemplifies research that is more "artful" in its efforts to deepen awareness of the interaction between physical intentionality and musical artistry. Interdisciplinary efforts such as this require the engagement of musicians, biomechanists, health experts, and others to improve music pedagogy, make music learning more efficient and effective, while simultaneously helping to reduce epidemic rates of playing-related injuries. The frameworks provided in this thesis takes a step in the direction of initiating "artful" biomechanics research in music performance. The research crosses disciplinary boundaries by considering what biomechanics of human movement and music performance can meaningfully offer each other. In doing so, it hopes to model applications of biomechanics that have the potential to change the way in which musicians interact with their instruments in order to effect artful performances.

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APPENDIX 1: INFORMED CONSENT

3D Quantification of Piano Technique

Biomechanics Laboratory

University of Lethbridge

We invite you to participate in a study that aims to quantitatively examine piano technique. Playing the piano is a challenging task. Even playing a scale, a fundamental skill, with proper technique and proper movement takes years of extensive practice to fully master. However, the knowledge of how pianists produce these movements has not been investigated extensively. As a pianists' technique improves, piano pieces become more technical, requiring continual daily practice to successfully perform the piece. Professionals spend hours a day repetitively practicing, which may predispose them to injury. Therefore, kinematic and kinetic data may give rise to knowledge of a pianist's health. This study uses the science of biomechanics and state-of-the-art motion capture analysis technologies to determine which movements are critical for successful technique and which movements expose pianists to musculoskeletal injuries. In this fashion, we can reveal the secrets of talented pianists and scientifically inform music pedagogy, while preventing a musculoskeletal injury from occurring.

The experiment takes approximately one to two hours. You will be asked to wear a black garment made of stretchable material, which covers the upper and lower body. Affixed to the garment will be 42 reflective markers (reusable), each with a diameter of 9mm. The garment will be washed between each participant use. Additional markers will be placed on the fingers and hands. Before the test, you will be allowed to perform a sufficient number of warm-up exercises to get used to the test environment and the piano. After warm-up, you will be asked to perform the protocol that was distributed to you one week prior to this study: three sets of scales and five sections from classical pieces at their respective tempos. During each trial, the kinematic (3D motion) and kinetic (force plate) data will be captured simultaneously. This data will be used to quantify your full body movement, the keys movement relative to your playing, and your pressure distribution during playing. This is similar to your performance and/or practice; therefore, there should be no risk for you during the test.

The information gathered from you during this study is considered confidential. To maximize your anonymity, you will be assigned a code, and this code will be used instead of your name at all times. Research assistants will also be required to sign a confidentiality agreement. All personal information (body weight, body height, age, and practice hours per week) will remain locked in a file cabinet that can only be accessed by researchers involved in this study and will not be disclosed without your permission. We may, however, wish to use your data measurements for a research presentation or educational purposes in the future. Your identity will be kept confidential. It should be mentioned that the twelve-camera system will not in any way videotape participants' faces, so that participants truly do remain anonymous.

Your participation in this study is entirely voluntary and you may withdraw from participating at any time. Should you decide not to participate in this study, your relationship with the Biomechanics Lab or any other department of the University of Lethbridge will not be affected in any way. If you choose to withdraw, any information collected from you up to the point of withdrawal will be deleted or destroyed. If you wish to see your performance analysis, we will supply you with a CD containing your 3D dynamic analysis data. For any further questions about this research, please feel free to contact Dr. Gongbing Shan, at (403) 329-2683 or g.shan@uleth.ca. Additionally, you may also contact Craig Turner, at c.turner@uleth.ca. If you have any further questions regarding your rights as a participant, please contact the University of Lethbridge Office of Research Ethics at (403) 329-2747 or research.services@uleth.ca.

Your signature below indicates that you have read and understood the information provided above, and that any and all questions you might ask, have been answered to your satisfaction. Your signature also indicates that you willingly agree to participate in this study, and that you understand you may withdraw from this experiment at any time.

I have read the attached Informed Consent form and I consent to participate in the "3D Quantification of Piano Technique" research study.

Printed Name: ______________________________ ***Date:*** ____________

Signature:______________________________

Witnessed by: ______________________________ Date:____________________

Note:

Would you like to have a CD copy of your 3D analysis Data? ☐ Yes ☐No

If yes, please leave your e-mail or phone # here: _____________________

After your data is processed, we will contact you to arrange a time to pick up the CD at the Biomechanics Lab.