Kinematic, Kinetic and Perceptual Analyses of Piano Performances

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Abstract

Expression is a central aspect in music performance. In order to fully understand its impact on the appreciation of the performance, it should be studied from the perspectives of the performer's body movements and audience' perception. Unfortunately, established pedagogical methods in classical piano rarely discuss strategies to integrate the movements from the whole body into structural and expressive parameters of music.

This dissertation examines the interactions between the instrument, the pianist' body movements and musical expression to help further the design of enhanced science-based pedagogical approaches to be used in piano lessons. The research proposes a systematic approach to study and analyze pianists' body movements when performing different pieces from the Romantic era, based on the analysis of the expressive and biomechanical aspects of the performance, as well as on the audience' perspective. We seek to understand better: 1) the relationships between pianists' body movements, timing strategies and structural features of contrasting Romantic excerpts in terms of technical level and character; 2) the cross-modal interaction between movements and acoustic parameters in the perception of piano performances; and finally 3) the biomechanics of upper-body movements in relation to musical expression and structural characteristics.

To address these questions, we combine kinematic and kinetic analyses, by means of motion capture and force plate technologies, as well as a multimodal analysis on audience' perception. First, an exploratory study was conducted with eleven pianists, each one performing a different piece from the Romantic repertoire, to evaluate the links between quantity of motion (QoM), force and the musical structure of pieces with various levels of technical difficulty, and to understand whether auditors are able to discriminate between different conditions when provided with one perceptual mode at a time (vision or sound) or both. Then, three pieces, selected from the original 11 pieces for their contrasting technical levels, styles and structural characteristics, were performed by ten different expert pianists. The experimental design was based on previous research that used different performance conditions to evaluate the effect of body movements on musical expression, and similarly the effect of different levels of expression on movements. Pianists' upper movements and postural control were investigated by measuring data derived from motion capture and force plate technologies, such as quantity, velocity and acceleration of motion, postural angles, vertical force, center of pressure (COP) displacements and velocity.

The results from Chapter 4 revealed that pianists' length of performance was less impacted by the QoM than by the level of expression regardless of the technical difficulty. Pianists conceive the different structural levels of a piece in similar ways, as recurrent expressive head movements across all pianists were found in specific areas of the scores. Chapter 5 showed that even slight modifications in the movements of pianists, such as acceleration and QoM of the head and torso movements, can have an impact on sound features, such as key velocity and phrasing, in a way that is perceptible for musically trained auditors. Perceptual and acoustical impact on expressive features, as key velocity and phrasing differed between a normal condition and an immobile condition. However, as Chapter 6 demonstrated, mentally restraining the movements does not impair pianists' postural control, as the COP displacements were not affected, whereas playing with an exaggerated level of expression may affect stability.

These findings show that incorporating a more scientific approach in piano lessons that consider kinematic, kinetic, perceptual and expressive aspects of pianists' performances, can lead to the design of a coherent pedagogical framework better adapted to students' individual needs, centered on the development of students' communicative skills and the integration of the whole body movements.

Keywords: Pianists' movements, Expression, Musical structure, Pedagogical applications, Motion capture, Force plate

Résumé

Un des aspects les plus essentiels en interprétation musicale est l'expression. Afin de bien saisir son impact quant à l'appréciation de la performance, elle se doit d'être étudiée du point de vue des mouvements du corps de l'interprète et de la perception du public. Malheureusement, les méthodes pédagogiques en piano classique abordent rarement des stratégies qui intègrent les mouvements du corps entier dans la communication des paramètres structuraux et expressifs de la musique.

Cette thèse examine les interactions entre l'instrument, les mouvements du corps du pianiste et l'expression musicale afin de concevoir de meilleures applications pédagogiques pouvant être utilisées dans les leçons de piano. Ce travail de doctorat propose une approche plus systématique afin d'étudier les mouvements corporels des pianistes jouant différents extraits de pièces romantiques, en se basant sur l'analyse des aspects expressifs et biomécaniques de la performance, ainsi que sur la perspective du public. Nous cherchons à mieux comprendre : 1) les relations entre les mouvements du corps des pianistes, le sens du timing, et les caractéristiques structurelles de différents extraits romantiques contrastants en termes de difficulté technique et de caractère; 2) l'interaction intermodale entre les mouvements et les paramètres acoustiques en ce qui a trait à la perception des auditeurs; et finalement 3) la biomécanique des mouvements du haut du corps en relation avec l'expression musicale et les caractéristiques structurelles.

Pour répondre à ces questions, nous avons utilisé des analyses cinématiques et cinétiques, au moyen de technologies de capture de mouvement et d'une plaque de force, ainsi qu'une analyse multimodale de la perception des auditeurs. D'abord, une étude exploratoire a été réalisée avec onze pianistes interprétant chacun un extrait différent issu du répertoire romantique afin d'évaluer les liens entre la quantité de mouvements, la force et les paramètres structuraux de pièces présentant divers niveaux de difficulté technique afin de déterminer si les auditeurs pouvaient distinguer différentes conditions de performance à l'écoute ou au visionnement, ou les deux. Trois pièces, parmi les 11 pièces interprétées par dix pianistes différents, ont été choisies pour leurs niveaux technique, leurs styles et leurs paramètres contrastés. La méthode expérimentale a été basée sur des recherches antérieures qui utilisaient différentes conditions de performance pour évaluer l'effet des mouvements du corps sur l'expression musicale, de même que l'effet de différents niveaux d'expression sur les mouvements. Les mouvements du haut du corps et le contrôle postural des pianistes ont été étudiés en mesurant des données dérivées de la capture du mouvement et de la plaque de force, telles que la quantité, la vélocité et l'accélération du mouvement, les angles posturaux, la force verticale, les déplacements du centre de pression (COP) et leur vélocité.

Les résultats du Chapitre 4 ont révélé que la durée des performances des pianistes était moins influencée par la quantité de mouvement que par le niveau d'expression, quelle que soit la difficulté technique. Les pianistes conçoivent les différents niveaux structurels d'une pièce de la même manière, puisque des mouvements récurrents de la tête ont été observés chez tous les pianistes dans des zones spécifiques de la partition. Le Chapitre 5 a démontré que même de légères modifications dans les mouvements des pianistes, telles qu'un changement au niveau de l'accélération et la quantité de mouvement de la tête et du torse, peuvent impacter les paramètres de son, tels que la dynamique sonore et le phrase, d'une manière audible pour les auditeurs entraînés musicalement. Cependant, comme démontré dans le Chapitre 6, le fait d'immobiliser consciemment les mouvements ne nuit pas au contrôle postural des pianistes, le COP n'étant pas affecté, alors que de jouer avec un niveau d'expression exagéré peut affecter la stabilité corporelle.

Ces résultats montrent que l'intégration d'une approche plus scientifique dans les cours de piano, prenant en compte les aspects cinématiques, cinétiques, perceptuels et expressifs des interprétations pianistiques, peut mener à la conception d'un cadre pédagogique cohérent, mieux adapté aux besoins individuels des élèves, et centré sur le développement des habiletés communicatives et l'intégration des mouvements du corps entier.

Mots clés : Mouvements des pianistes, Expression, Structure musicale, Applications pédagogiques, Capture de mouvement, Plaque de force

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Contributions of Authors

This thesis is formatted as a manuscript-based dissertation and includes three articles. The results presented in this thesis have been or will be published in the following publications:

Chapter 4 Massie-Laberge, C., Cossette, I. and Wanderley, M. M., "Kinematic Analysis of Pianists' Expressive Performances of Romantic Excerpts: Applications for Enhanced Pedagogical Approaches." in *Frontiers in Psychology*, vol. 9, no. 272, 2019.

Chapter 5 Massie-Laberge, C., Cossette, I. and Wanderley, M. M., "The Influence of Body Movements on the Auditory Perception of Piano Performances." (to be submitted).

Chapter 6 Massie-Laberge, C., Cossette, I. and Wanderley, M. M., "Pianists' Postural Sway while Playing Romantic Pieces in Unconventional Performance Conditions." (to be submitted).

Results also appear in the following publications:

– Massie-Laberge, C., Cossette, I. and Wanderley, M. M., "Motion Kinematics and Auditors' Perception of Expressive Gesture in Romantic Piano Performances." In *Proceedings of ICMPC 2016 International Conference for Music Perception and Cognition*, San Francisco, USA, 2016

– Massie-Laberge, C., Cossette, I. and Wanderley, M. M., "Hearing the Gesture: Perception of Body Actions in Romantic Piano Performances." In *Proceedings of ICMPC 2016 International Conference for Music Perception and Cognition*, San Francisco, USA, 2016.

– Massie-Laberge, C., Cossette, I. and Wanderley, M. M., "Kinetic Analysis of Hip Motion During Piano Playing." In *Proceedings of 5th International Conference on Movement Computing* (MOCO'18). ACM, New York, NY, USA, 2018.

My contributions to these articles consisted of designing and carrying out the research projects, which included the conceptualization of the hardware and software setup and synchronization protocol, collecting and processing data, completing quantitative and qualitative analyses, and writing the reports for publication. The design of the experimental methods was realized by all the authors. My advisors Isabelle Cossette and Marcelo W. Wanderley were responsible for the supervision of the research throughout all the projects, the review of the reports, and the edition of the dissertation and articles. They provided funding, laboratory space and equipment (Music Performance and Body Lab – MBPL and Input Devices and Music Interaction Laboratory – IDMIL). The work presented in Chapters 4 and 6 describes the importance of examining various pieces from the same style with the same group of participants. The results showed that the technical difficulty characterizing each excerpt had an important effect on pianists' capacity to modulate the quantity of motion during each performance condition. Moreover, the findings from Chapter 5 have led to a better understanding of the impact of body movements on the acoustic results and the perception of the performances. This information is important for the field of piano pedagogy as it can help teachers provide more systematic feedback regarding the links between movements, posture, musical expression and structure during lessons. It can also help students make independent creative choices and hopefully increase their musical communicative abilities according to the musical context.

The three studies presented in this thesis were carried out in accordance with the recommendations of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans, McGill University Research Ethics Board II (REB II). All participants gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the McGill University Research Ethics Board II, a unit within the Office of the Vice-Principal (Research&Innovation). REB File number: 101-0815.

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List of Acronyms

AP	"Anterior-posterior"
CEUS	"Contrast-Enhanced Ultrasound Systems"
COP	"Center of Pressure"
DAW	"Digital Audio Workstations"
IOI	"Inter Onset Interval"
LTC	"Linear Time Code"
MIDI	"Musical Instrument Digital Interface"
ML	"Medial-lateral"
MOCAP	"Motion Capture"
MTC	"Midi Time Code"
OSC	"Open Sound Control"
RMS	"Root Mean Square"
RGB	"Red Green Blue"
QOM	"Quantity of Motion"
QTM	"Qualisys Track Manager"
SD	"Standard Deviation"
SMPTE	"Society for Motion Picture & Television Engineers"

Chapter 1

Introduction

1.1 Statement of the problem

1.1.1 The feedback of the instrumental teacher

Instrumental teachers play a central role in the development of students' musical communicative abilities. However, the teacher's guidance rarely explicitly connects the student's body movements to structural and stylistic features of a piece [135, 137, 268]. Altenmüller and Gruhn [5] found that in instrumental teaching, the principal focus is on the development of motor and technical skills, more precisely on the automation of patterns of movement. Indeed, teachers devote more time to technical work than to expressive issues, which can be associated with the "instrumental-technical" approach [121]. Rostvall and West [209] indicate that teachers who focus more on technical skills at the expense of expressive aspects of music might lead students to question their own musicality or abandon musical studies. Moreover, it was shown that the brain learns best if it actively participates in exploring and experimenting with musical features and gestures [109, 227]. In other terms, for learning to occur, students need to be actively involved in the instrumental lesson. To encourage students to focus principally on their musicality could allow them to feel more implicated [150].

If music teachers encounter difficulties while attempting to provide pertinent information to students concerning expressive skills, this is mostly due to the fact that music pedagogy has suffered from a lack of explicit theories that could guide the teaching of expression and bodily communication [137]. As emphasized by Tait [228], teaching of expression could benefit from the inclusion of more explicit goals, systematic teaching patterns, and specific feedback. Using the available technologies to study musical expression in relation to expert pianists' body movements and musical structure could help develop a coherent pedagogical framework to be used in piano lessons. Teachers could benefit from a better understanding of the physical and acoustic strategies that expert pianists used to convey information about the musical structure and expression. To integrate this information during lessons could help students analyze the nuances of their body movements and connect them to specific structural aspects of the music and to a precise expressive intention.

1.1.2 Piano pedagogical theories

Piano pedagogical method books most often focus on the technique of localized body movements, such as the hands, arms and shoulders (e.g. [51, 113, 151, 178]). Moreover, several recent studies have been conducted on the kinematics and kinetics of upper-limb movements while pianists use different types of touches, at various tempi or sound dynamics [80, 84, 144, 238], and on hand and upper-limb injuries [83, 212, 267]. However, the question of how ergonomic factors of instrument playing influence biomechanical interactions and bodily expression remains largely unanswered. It is worth mentioning that, to the authors' knowledge, almost no studies have been conducted on how pianists adjust their upper body movements, posture or certain kinetic parameters, such as the force applied on the stool, in relation to musical expression and structural elements of music. This lack of studies suggests that further research is needed to determine the extent to which expert pianists use the whole-body movements and adapt their posture relatively to structural elements from various pieces of music.

1.1.3 Audience perception

It is common knowledge that musicians' body movements may help audience members better understand the musical structure and the performer's expressive interpretation of music [54, 247, 255]. Dahl and Friberg [54] have demonstrated that a close correspondence exists between movement and audio cues for the four basic emotions (i.e. anger, sadness, fear, happiness). Indeed, body movements allow listeners to extract visual information that brings a better understanding of the performer's emotional intentions.

Unfortunately, during instrumental lessons, students do not have the opportunity to directly compare their playing with an optimal performance (e.g. [7, 134, 187, 224]). It is difficult for them to deduce the relationships between their expressive intentions and body movements and the listeners' perception. According to Juslin and Persson [135], teachers would benefit from the inclusion of a pedagogical model that would help students establish better communication between them and listeners. Indeed, the integration of feedback on gestural and acoustic features of the performance could possibly improve musicians' expressive communication by providing them with a better understanding of the acoustical and movement cues that may convey specific emotions. Although research has focused on the cross-modal interaction between sight and sound in the perception of musical performance, none has explored how a modification in body movements may affect both expressive features and auditors' perception of the performance.

1.1.4 Experimental design and technologies

Experimental knowledge concerning pianists' performance is framed by the devices developed to measure its physical parameters. Infrared motion capture systems, such as Qualisys or Vicon, have been commonly used to study pianists' upper body, arm, hand and finger movements [56, 57, 105, 106], as well as other passive systems, such as the Kinect [9], or image motion capture with paint markers [157]. Sensor systems have also been attached to the instrument to analyze parameters related to finger movements or piano touch (e.g. [11, 108, 166]). Moreover, electromyography (EMG) was used to measure muscular activity at different joints in the arms and hands [81, 82, 84]. To our knowledge, no previous studies have examined the interaction between the kinematic and kinetic aspects of pianists' performances with both motion capture and force plate technologies. Combining both technologies can help acquire more data with regard to pianists' kinematic and kinetic aspects of their performances.

Previous research has investigated the relationships between musical structure and pianists' body movements (e.g. [28, 157, 220, 232]). However, most of these studies based the interpretation of their results on one single musical piece or excerpt, Chopin Preludes in particular, which does not allow evaluation of the same group of pianists reacts physically and expressively with regards to different pieces of music. The design of our methodology was similar to previous research to build upon these results, but used various musical excerpts from the Romantic repertoire. Studying how excerpts with different levels of complexity are performed by the same pianists, as will be reported in this thesis, could lead to a better understanding of how auditors perceive and react to gestures and expression distinctively.

1.2 Objectives of this research

Experimental research has previously been conducted on pianists' body movements to provide information about the biomechanics of piano playing, the links between expression and musical structure, and audience perception. Many challenges still exist in coming to a complete understanding of: 1) the relationships between pianists' expressive body movements and structural elements of technical pieces of music; 2) the cross-modal interaction between kinematic and sound features in the perception of piano performances; and 3) the biomechanics of upper-body movements in relation to musical expression and various excerpts.

In this dissertation, we address these questions by combining kinematic and kinetic analyses by means of motion capture and force plate technologies, as well as a multimodal analysis on audience perception. Our research focuses on different perspectives (i.e. music performance, audience and biomechanical) to propose a systematic approach to analyze pianists' body movements that can be applied to various pieces of the Romantic repertoire.

The objective of the first study was to identify the relationships between kinematic and timing parameters used by pianists to convey expression and information about the musical structure of pieces with different technical levels and musical contexts. We also evaluated how consistent pianists are among themselves while performing these different pieces. The goal of this research was not to assess whether pianists express their musical ideas intentionally or not, but to observe the trends and differences among a group of experienced pianists and how various musical excerpts influence body movements and expression.

The second experiment sought to evaluate the effect of a performance where pianists consciously reduce their movements while trying to produce a natural expressive result on auditors' perception and acoustic results.

Finally, the last study investigated the relationships between kinematic and kinetic aspects of expert piano performances in order to clarify how pianists' postural sway is used in different musical contexts.

Ultimately, the aim is not to prove any universal truth or to impose a specific way of playing to be taught in piano lessons, but to provide a better understanding of pianists movements in relation to the musical score. This clarification will help reconcile the evidence-based knowledge with the current pedagogical approaches. The combination of kinematic and kinetic analyses, as well as a multimodal analysis on audience perception, can shed light on individual and shared communication skills in piano performance. Finally, the analysis of the structural elements from various pieces of music in relation to expert pianists' expressive body movements can contribute to the design of a coherent pedagogical framework to be used in piano lessons.

1.3 Thesis structure

Chapter 1 presents the introduction: section 1.1 provides the statement of the problem. Section 1.2 discusses the objectives of the research and section 1.3 exposes the thesis structure.

In **Chapter 2** is presented an overview of the most relevant literature: section 2.1 describes the pedagogical theories in piano performance and other kinesthetic approaches. Section 2.2 discusses the classification of the different terminologies used to describe the notion of gesture in music performance, with a specific focus on piano performance. Finally, section 2.3 provides a description of the different technologies and measurement systems that were previously used to study the interactions between musicians and their instrument, with their respective advantages and disadvantages examined. The purpose of this chapter is to help the readers comprehend the various analysis methods and technologies used to study the role of body movements in piano performance so that they can understand the reasons for which specific parameters were selected as variables to test in the studies.

Chapter 3 presents the exploratory study that was conducted as a preliminary study to help justify the choice of musical excerpts that were used for this research. The study examines the auditors' ability to discriminate between different performance conditions when provided with different perceptual information (i.e. visual, audio or both) and analyze pianists' quantity of motion (QoM) and force data in relation to different expressive conditions and excerpts. The reasons for choosing the Romantic excerpts are discussed in this chapter and were based on the pianists' quantitative measurements and auditors' perceptual results.

In **Chapter 4** we evaluate how pianists modulate their performance in terms of QoM and duration when performing the excerpts in various expressive conditions. From the exploratory-study results, three Romantic excerpts were chosen and used for the experiment. We discuss the patterns of recurrence on motion data during the performances. Finally, we evaluate pianists' own conception of their body movements and the link with the musical structure.

Chapter 5 investigates both the perceptual and kinematic aspects of the performances. The quantitative measurements of pianists' movements and acoustic features are compared to the results from the auditors' perception analysis.

Chapter 6 presents how the relationships between kinematic and kinetic aspects of pianists' performances vary according to various musical contexts. We also examine the effect of different performance conditions and musical structure on pianists' postural sway.

Chapter 7 summarizes the results on pianists' body movements, postural sway and audience perception in relation to previous studies conducted on musicians' movements, musical structure and expression.

Chapter 8 presents the main contributions of the thesis and discusses the limitations of the research, as well as further work in light of the results obtained and few concluding remarks and pedagogical considerations.

Chapter 2

Background

In this chapter will be first discussed the current situation in music pedagogy and the kinesthetic methods used in instrumental lessons, as well as the limitations of such approaches. Second, we will review some of the current definitions of the term 'gesture' and the different functional aspects of music-related body movements. Finally, various technological tools and methods to study pianists' movements will be discussed.

Piano pedagogy can benefit from a scientific perspective that takes into consideration the study of the kinematic, kinetic and perceptual aspects of a musical performance. Unfortunately, music pedagogical theories still lack scientific knowledge that could guide the teaching of expression [137] and posture [211]. Moreover, piano teaching approaches can differ significantly from one teacher to another, which can cause confusion for students learning how to integrate simultaneously several aspects related to performance, such as body movements, expression, and musical structure. Technologies and scientific methodologies can help analyze and describe better pianists' body movements and eventually help teachers provide more effective strategies in instrumental lessons.

2.1 Pedagogical theories in piano performance and other kinesthetic approaches

Despite the advances in biomechanical analyses of musical performances in the last century, pedagogical theories still do not integrate many important aspects related to the performance and the body [267]. Studies have revealed the importance of the inclusion of an accurate biomechanical movement education as soon as possible in the training of musicians at all levels and a better understanding of the outcomes [18]. Indeed, it was shown that the quality of an ergonomic playing posture may have an essential role in musicians' ability to play expressively [160, 179, 258, 267]. In this section, we will approach some biomechanical concepts of pianists' posture, as well as somatic and pedagogical methods that focus on acquiring an awareness of body motion, while discussing certain issues related to these approaches.

2.1.1 Biomechanical concepts related to pianists' posture

In piano performance, the effect of posture can have a major influence on the amount of muscular effort needed to play. For instance, an optimal posture implies that the spine is straight and fully erect with the pelvis in equilibrium [136], which minimizes the muscular effort needed to maintain the posture. When the torso is flexed toward the keyboard and the cervical spine is extended, which occurs when the stool is placed too far from the keyboard, it augments the kyphosis of the thoracic spine, while the pelvis is tilted posteriorly (Figure 2.1). This creates muscular tension because the center of mass of the upper body is pushed forward [136, 253]. An increased tension in the shoulders is felt due to the center of gravity of the trunk that is shifted forward. On the other hand, when the stool is placed too close to the piano, lumbar lordosis increases, the shoulders and elbows are sent behind the torso, inducing a forward tilt of the pelvis. This augments the muscular effort needed, as well as the risks of developing low back pain, and even limits breathing movements [253]. In addition, the elbows are pushed backward, which confines the movements of the hands from side to side. If the stool is set too low or too high, the wrist joint may tend to be overflexed or overextended. This can have an impact on the flexibility of movements of the fingers. A hunched posture may also generate an unnecessary tension in the shoulder and neck, interfering with the correct use of certain muscles in these regions when they are required [17].

These biomechanical principles show how important it is to integrate methods, in instrumental lessons, that would help students acquire self-awareness of body-alignment in order to enhance the overall posture when performing.

2.1.2 Somatic techniques

To increase kinesthetic awareness during performance, many musicians have turned to somatic training techniques, such as body mapping [47], the Feldenkrais method [76] and the Alexander Technique [3]. Other techniques are being used to help students develop the perception of rhythm, such as the Dalcroze eurythmics [125], or to avoid tensions through fluent movements, such as the Taubman technique [74]. These methods can help students develop healthy playing techniques and equip them with detailed knowledge of the body's structure and function [46, 225].

Body Mapping

Body Mapping was shown to be effective for enhancing musicians' expression, technical skills and artistic ideas [18]. While observing his students in his cello lessons, William Conable showed that patterns of student's movements were consistent with their perception

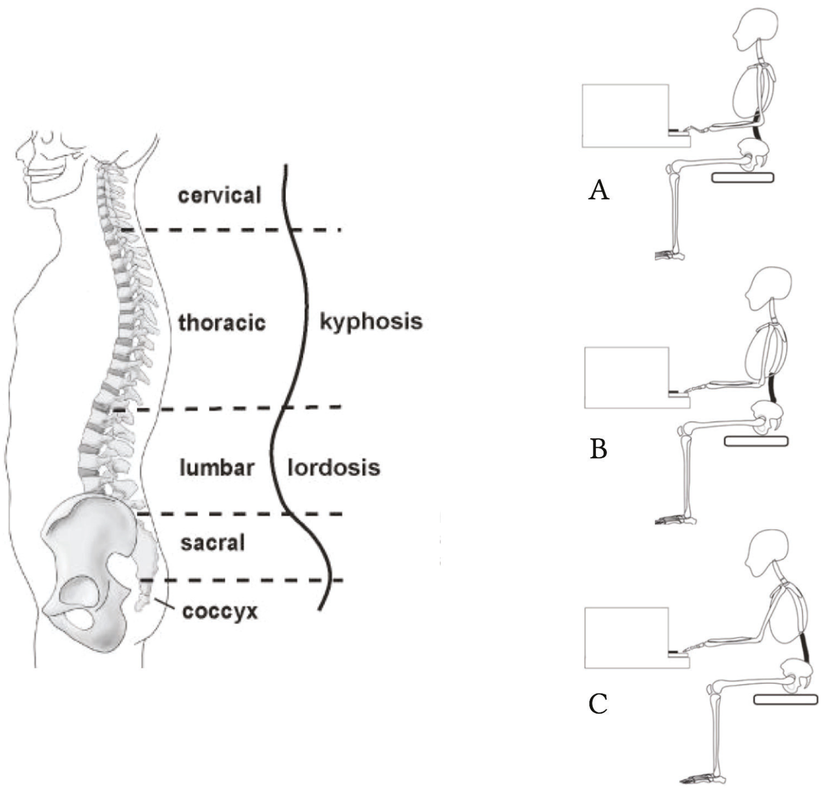

Fig. 2.1 (Left picture) The spine and pelvis from the sagittal point of view. The vertebral column is divided into five regions: seven cervical vertebrae constitute the neck; twelve thoracic vertebrae support the ribs; five lumbar vertebrae; four coccygeal vertebrae; and the coccyx. (Right picture) Three different pianist' sitting postures: **A** the stool is set too close to the piano, which occasions an increase in lumbar lordosis. This posture restricts arm movements and the shoulder may even have to be raised to maintain the forearms horizontal; **B** the stool is set at an optimal distance from the piano, which allows the pianist to place the upper arm close to vertical; and **C** The stool is too far from the piano, forcing the pianist to extend the upper arm in an exaggerated way that creates unnecessary muscular effort. Kyphosis of the thoracic spine thus increases and the neck is extended (Watson, 2009) (Reprinted with permission from Scarecrow Press).

of their body and also with how they conceived its structures and functions instead of how they were actually structured [131]. He called this approach "body map". Neuroscientists understand body maps as neural networks that consist of one's internal representation of the cortical surface of the brain in relation to the anatomy of the body [116]. This approach seeks to integrate kinesthesia into sensory awareness and to provide musicians with the physical skills for embodied performing [131, 159]. Student-participants revealed that to learn this method during a semester improved their communication of musical expression (i.e. dynamic and phrasing control, faster tempi precision, richer tone quality), as well as their technical skills attributed to a better biomechanical use during technical passages. Although body mapping emphasizes inclusive awareness, which advise students to control and direct their attention, it does not guide student-performers to map parts of their body to specific elements of the musical structure and reflect on how this relationship can affect their expression.

The Alexander technique and Feldenkrais method

The Alexander technique and Feldenkrais method are both somatic techniques that reinforce the awareness of movements with the objective of helping people become more kinesthetically aware of the functions of movements that are part of everyday life. They are often used in music performance to ease the fluidity of movements, reduce muscular imbalances and limit overuse injuries [124]. They theorize that movements from everyday life can lead to movement disorders, pain and overall patterns of dysfunction, and that these issues can be resolved through a learning process. Although they are based on similar principles, they are distinct in their philosophy.

The Alexander technique [3] postulates that, by inhibiting routine movement, a person can reset the action and relearn to move more naturally. The expected results of this approach are the improvement of movement, posture or voice quality, and decrease of pain. The technique stresses the importance of the relation between the head, the neck and spine to control efficiently body gestures. This idea is described as primary control, where the upper and lower extremities are considered as less essential for an overall well-being. This technique has been applied with performing musicians, who are often subject to physical and mental strains and stresses. In several studies (e.g. [71, 173]), the Alexander Technique helped improve respiratory functions, by teaching the student how to use efficiently the musculoskeletal system. In addition, positive effects of the Alexander Technique were observed for physiological performance. An improvement related to the overall musical and technical quality was shown in subjects [124]. Generally, the role of the teacher, even if the latter is only familiar with the Alexander concept but still concerned in improving bodily use, would be to help the student become aware of maladaptive reactions that are associated with underlying patterns of tension and anxiety, and mostly to encourage fluidity and ease of movement.

While the Alexander technique gives a clear importance to incorporating a dynamic posture in the learning process, the Feldenkrais method [75] does not address posture directly. The technique is often taught in a supine position to suppress gravity. Feldenkrais incorporated the terms awareness through movement, where the instructor will verbally guide a group of students or individuals through a series of movements to explore and integrate the relationships between body posture and space, and functional integration, which includes the sense of touch to ease the movement awareness [124].

Jaques-Dalcroze's approach

Jaques-Dalcroze's method, or Dalcroze eurythmics, focuses on teaching the perception of rhythm to students through body movements [125]. Music students learn to internalize various rhythmic patterns through physical movements in time and space. Jacques-Dalcroze's theory also emphasizes the fact that the body is inseparable from the mind. One of the particularities of the method resides in the evocation of sensations that create mental images. He claimed that music is the most powerful means of education and can improve the communication between the senses, body movements and the mind. To use rhythmic and kinesthetic exercises in class could help students gain physical awareness. Experiencing the beat or pulse of music, for example, by swinging movements away from the instrument, like in the case of piano performance, may help embody the full motion required to produce the exact attack point on the beat and also feel the approaching downbeat [66]. This approach should be further investigated with different musical contexts in order to understand how moving according to various rhythmic patterns can help enhance performers' musical expression.

The Taubman technique

The Taubman technique catalogs the micro-movements characterizing a fluent technique that many virtuosi adopt and integrates a systematic approach for the development and coordination of healthy movements, by encouraging pianists to consciously analyze their movements [74]. Dorothy Taubman studied anatomy, physics, physiology, the mechanisms of piano, as well as Ortmann's scientific analysis of piano technique [160]. Her research also contributed to the analysis of playing-related musculoskeletal disorders (PMRDs) and their causes in the late 1960s. The main principles that constitute her approach are: 1) a kinesthetic awareness; 2) a biomechanical coordination that uses all body parts involved near their midrange of action; 3) an economy of effort to alleviate tension; and 4) a focus on precision and freedom. The approach focuses on seating, alignment and hand position in order to reinforce a healthy coordinated technique that limits tension from the hands, arms and shoulders. This method may help student-performers understand that tensions are not a necessary part of bodily expression.

Issues in piano pedagogy

Although the pedagogical methods mentioned above can help musicians with postural control and expressive communication, they do not advise students with regard to how to move their body in relation to the structural elements of music. Moreover, pedagogical literature on piano technique rarely integrates guidance specifically related to the posture of the whole body, but rather focuses on localized body movements, such as the hands, arms and shoulders (e.g. [151, 178, 267]), and the proper technique to adopt to avoid injuries (e.g. [83, 212]). Knowing that most of the musicians' movements have a strong connection with specific structural parameters, pedagogical approaches should include biomechanical concepts related to pianists' posture, along with a clearer perception of the links between movements and musical structure. This would lead to a better understanding of the performer's expressive possibilities and postural constraints brought by the instrument.

To understand more about the various functions of music-related body movements, we will first discuss the different viewpoints and terminological considerations surrounding the notion of 'gesture' in music research. We will end this chapter by discussing various technologies and methodological approaches that can be used to analyze further body movements in music performance.

2.2 Music-related gestures in piano performance

In the music community, the term 'gesture' has been widely used but often in different contexts and has been discussed through various perspectives on the analysis point of view (i.e. performer, audience or instrument interaction). According to Leman [150], gesture research related to music seeks to understand the biomechanical and psychomotor factors that describe human movement in the context of music performance and perception.

However, the definitition of gesture varies across researchers from different backgrounds. For instance, in linguistics and psychology, the term 'gesture' is used to communicate meaning in social interaction, whereas in human-computer interaction (HCI) and computer music it is used to interact with a computer-based system [127]. Based on the models from McNeil [164] and Zhao [271], Jensenius [126] has suggested a tripartite division of gesture research to ease the understanding of the different gesture definitions:

- **Communication gestures** are considered as means for social interaction and human communication. This definition is often used in linguistics, psychology or social anthropology.

- **Control gestures** are interpreted as the communication between humans and computers, and the possibilities (i.e. what can be communicated) for controlling various interactive systems. The term is often found in human-computer interaction (HCI), computer-assisted music.

- **Mental imagery gestures** are studied as perceptual processes, and do not refer strictly to physical body movements. They can be the results of physical movement, sound or other types of perception. This definition is mainly found in cognitive science, psychology, musicology.

However, many research fields that focus on the study of human movements do not discussed the term gesture at all, such as the fields of kinesiology and biomechanics, or in some music performance literature, in which the terms motion or movement are preferred [41, 60, 85] and expressive movement [61, 191]. Leman [150] also introduced the term corporeal articulation, referring to various types of music-related movement. The term was borrowed from Truslit [241], who considers corporeal articulations as a way to express the inner motion generated by music.

The many gesture definitions in the different musical fields have brought a certain confusion regarding how and when the term gesture should be used in scientific research. To avoid this confusion, music researchers have suggested to use gesture in combination with another term, such as instrumental gesture [23] or ancillary gesture [250]. Therefore, in the context of music performance, a taxonomy of gestures was elaborated, based on their functional aspects. In a study conducted on the playing technique of the pianist Glenn Gould, Delalande [67] proposed a three-tiered classification of musical gestures, that can be placed on a spectrum from observable actions to mental images:

- **Effective gestures** are essential to mechanically produce a sound on a musical instrument(e.g. bow, blow, press a key) and corresponds to the instrumentalist' playing technique.
- **Accompanist gestures** refer to the body movements related to effective gestures (e.g. chest, elbow movements, breathing for a piano player) and possibly important for a performer's physical comfort and ergonomic fluidity.
- **Figurative gestures** are purely symbolic and perceived by audience members through the produced sound. They can be described as metaphorical gestures, and are not systematically associated to the physical actions of a performer. For instance, an arpeggio can be imagined as one gestural movement from one point to another in the pitch space.

Figure 2.2 shows a schema based on the research of Delalande [67], Cadoz [23], Wanderley [251] and Jensenius [126] and designed to ease the understanding of the different terminologies and functional aspects of the term 'gesture' used in the musical literature, namely in human-computer interactions, music performance, music cognition and music

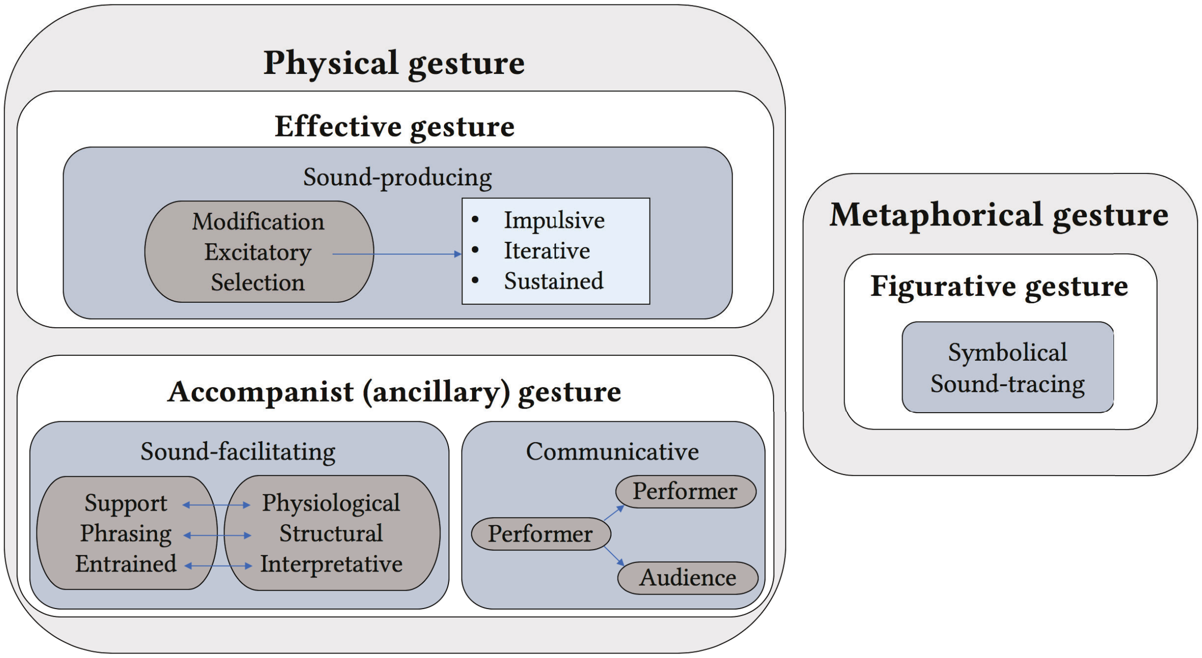

Fig. 2.2 Conceptual schema based on the research of Delalande [67], Cadoz [23], Schaeffer [214], Wanderley [251] and Jensenius [126] of the taxonomy of musical gesture.

perception. This section aims to describe each one of these categories according to the perspectives of different fields of musical research, and finally discuss how they relate or not to piano performance.

2.2.1 Effective gestures

As Delalande [67] proposed, effective gestures can be defined as the movements an instrumentalist executes to produce sound. This category of gestures is distinct from the others, as it is based on the fundamental physical actions applied to the instrument that are necessary to play [251]. Table 2.1 shows the various uses of effective gestures in the literature. They refer to the direct modifications applied to the quality of the sound, or more specifically, as the physical changes applied to the instrument itself.

Table 2.1 Effective gestures

-Excitation and modification applied to the quality of the sound and to the instrument [126]
-Movements executed with the hands and arms -Are part of the performer's technique and movement strategies [53]
-Instrumental gestures applied to a material object with which there are physical interactions -Are semiotic, ergotic, or epistemic -Are divided into: excitation, modification, and selection [25]
-Mechanical models that interact with the instrument (or simulated instrument) and that produce sound [91]
-Aligned to the instrumentalist's technique -Effectively produce sound -Provide a feedback to the performer [67]
-Excitatory gestures that have biomechanical phenomena in sound-production: impulsive, sustained, iterative [214]
-Combination of the excitation phase (contact with and energy transfer to the instrument) and the movement trajectory [95, 97]

According to Cadoz and Wanderley [25], sound-producing gestures are a) semiotic in that they help listeners understand and appreciate the information conveyed by the sound; b) ergotic, as they make use of the body (hands, lips, feet) and are in direct contact with the instrument; and c) epistemic, since performers use their tactile-kinesthetic perception to play the instrument. Cadoz [23] suggested a taxonomy that divides effective gestures into subcategories based on their sound-producing functions: excitatory, modification, and selection gestures.

Sound-producing functions

Excitatory gestures Excitatory actions refer to hitting, stroking, bowing, blowing, kicking, and singing. According to Jensenius and colleagues [128], the excitation gestures may be direct or indirect. In the direct condition, a harpist, for instance, is in direct contact with the vibratory material of the instrument. However, for pianists, a complex mechanism separates the player and the production of the sound. In Shaeffer's typology of sonorous objects [214], three categories of excitatory gestures have distinct biomechanical phenomena in sound-production: impulsive or instantaneous (i.e. a discontinuous effort and transfer of energy, which often results in a sound with a sharp attack followed by a longer or shorter decay); sustained (i.e. a continuous effort and transfer of energy, such as in a long bow movement); and iterative (i.e. a fast repetition of sound onsets, such as in a tremolo).

Modification gestures Modification gestures are gestures that modify the instrument's sound properties. For instance, sound-modifying actions relate to changes of pitch (e.g. for vibrato making by left hand movements on string instruments) or timbre (e.g. by shifting bow positions on string instruments).

Selection gestures The selection gestures consist of gestures that are used to select different elements in an instrument. They do not directly provide energy to produce the resulting sound, and do not bring modification to the instrument's properties (i.e. a particular fingering at the piano, where the performer has to choose specific keys for selecting a note).

2.2.2 Accompanist or ancillary gestures

Also known as ancillary gestures [249], accompanist gestures are characterized by most researchers as movements that are not directly involved in the sound production (Table 2.2). Several studies have analyzed performance gestures (e.g. [60, 67, 249]) showing that musicians not only use skilled movements to produce sound, but also movements that do not relate directly to sound generation.

Wanderley [251] proposed a typology that categorizes ancillary gestures in three different

Table 2.2 Accompanist (ancillary) gestures

-Not carried out with a specific intention other than being the results of sound-producing gestures -Have a sound-facilitating function [128]
-May affect the production of notes or phrases -Are not communicative nor involved in sound production [53]
-Expressive movements not directly involved in sound production -May be associated to structural features of the music -May be important for a performer's physical comfort and ergonomic fluidity -Enhance the performer's emotional experience [67]
-Not necessary for sound production -Solely include gestures applied to the instrument -Are divided into: physiological, structural, and interpretative [251]
-May be related to the music, but have nothing to do with the resulting sound -Facilitate the performance and help avoid fatigue, shape expressive or articulatory features in music [95]

factors: physiological, structural, and interpretative. These typological elements can be associated with a sound-facilitating function, namely support, phrasing and entrained [126].

Factors and sound-facilitating functions

Physiological Physiological or ergonomic factors are responsible for postural adjustments in order to prepare the movement. These gestures may be important for a performer's physical comfort and ergonomic fluidity in performance [67]. For instance, pianists determine the trajectory and velocity of the finger before the key is actually struck. Not only the motion of the finger is planned, but also the circular movement of the elbow that enables larger hand displacements [126]. In clarinet performance, when breathing occurs, the instrument is brought down to a vertical position [250]. Moreover, it was shown that pianists also anticipate the tone earlier both mentally and physically. For Shove and Repp [200], the sonic event actually starts at the same time that the gesture is initiated, before the contact with the keys. This kinesthetic feeling accompanying the gesture is the result of muscular adjustments made to control the sound.

Physiological gestures would be linked to a function of *support* [126]. Support gestures play a role in shaping the sound and helping the performer feel more stable (Table 2.3) [53, 128, 192]. For instance, pianists often take a preparatory upbeat breath right before starting to play [143]. They may use certain body movements to play a technically difficult musical passage, to emphasize the harmonic or melodic structure, or to control micro-fluctuations of tempo and dynamics [192].

Structural Many studies on piano performance connect expressive body movements to the musical structure. For example, Clarke [37] mentions that temporal organization of music can be perceived in pianists' body sway. Indeed, a clear periodic movement has been associated to a specific musical context and rhythmic structure [157]. Pianists' head and torso tilt has been shown to accentuate certain points in the melody [126], and harmonic progression [232]. Moreover, pianists often use elbow circles, incline the head, use wrist pulsations and body sway on the main beats [192]. Head and shoulders may also describe a continuous approximate oval shape movement toward and away from the piano over the period of one or two bars, while hand lifts are also used to emphasize the end of phrases. Finally, Davidson [62] found that there were consistencies in the timing of pianists' movements at very specific point in a piece (e.g. phrase boundaries, climax).

Studies on clarinet performance have also shown that bell motion reinforces idiomatic acoustic events at phrase boundaries [186, 252]. Certain gestures also help anticipate the beginning of new sections, for instance when the performer initiates a breathing movement at the clarinet, while other movements may create the impression that the phrase extends beyond the end of the note [246]. These physical gestures can contribute to the experience of tension, sense of phrasing and expectations.

Structural factors would be associated to a function of *phrasing* [126]. Phrasing movements are closely linked to the phrasing structure of the piece. As Wanderley [251] demonstrated, ancillary movements are repeatable, meaning that even after a certain amount of time, performers can reproduce similar patterns of expressive movements in relation to the musical structure. It was shown that these repeatable movements are closely connected to phrasing boundaries.

Interpretative Performance requires musicians to internalize their interpretation of the musical structure, including parameters such as phrasing, harmonic modulations, and section boundaries. Moreover, despite idiosyncratic body movements, musicians perform similar and repeated patterns of motion that conform to the underlying phrasing structure of the pieces. However, performers are not necessarily aware of the particular gestures they use that convey extra information to the audience [249]. A good example of interpretative and structural ancillary gestures' analysis is the one provided by Delalande (Delalande, 1988) on Glenn Gould's gestures. Delalande observed that Gould's left hand unique movements in Bach performances suggest a precise analysis of the score. Gould often emphasizes syncope and anticipates phrases, by a preparation with a vibrato of the hand, or a release on the strong beat (rise with the hand). Every change of type of gesture may be related to a change in the composition or in the articulation, and thus, may serve as a guide for the auditors through the musical structure.

Interpretative factors would be linked to an *entrained* function. Entrained gestures refer to the synchronicity of the body and the music, for instance when tapping the foot, nodding the head, or swaying the body. These gestures may be important for performing with the appropriate timing, as it was shown that removing certain body movements in a performance may affect the duration of the performance [252].

Table 2.3 Sound-facilitating gestures

-Shape the resulting sound -Are divided into: support, phrasing, and entrained [128]
-Neither communicative nor directly involved in sound production -Stabilize the performer's body [53]
-Help play technical musical passages -Have a spatial dimension (i.e. the upper body will follow the movements of the hands to help play a melody) [192]

Communicative function

Another function of ancillary gestures is the intention of communicating something either between performers or between a performer and an audience. Communicative gestures seem to be used only for visual communication (Table 2.4). They ease observers' understanding of the structure, pitch relations (e.g. dissonance), fill or break expectations [233], and convey emotional state [135]. Moreover, specific emotions can be communicated through various levels of gestures [52, 54]. For Jensenius and colleagues [128], facial and vocal expressions are considered the most important gestures in (emotional) communication. According to Davidson and Correia [64], communicative gestures are not only used for engaging with the audience, but also to communicate with co-performers. Performers use movement patterns to coordinate timing, dynamics, and other expressive features with co-performers. From the perspective of both the auditor and the performer, all performance gestures can have a communicative function [128], or a semiotic function [25]. Communicative gestures implicate social interactions between both co-performers and the audience and involve performers' and auditors' individual experiences at the same time.

Table 2.4 Communicative gestures

-Intended for communication -Are divided into performer-performer and performer-perceiver interactions [128]
-Used for visual communication (e.g. emotions) [52, 53]
-Encompass four different aspects: individual communication, communication with co-performers, performer's personal experiences, and interactions with audience [64]

2.2.3 Figurative gestures

According to Delalande's third category of gestures, figurative gestures are perceived by the audience through the produced sound, but without necessarily a direct correspondence to a movement (Table 2.5). They can be described as metaphorical gestures, not systematically associated to physical actions of a performer.

Recent neurocognitive research supports the idea that motor images are inherently connected to sound-perception [145]. Motor imagery, also referring to images of effort and kinematics needed to produce a sound, plays an essential role in the perception and cognition of musical sound [94, 97]. These concepts take roots in Liberman's motor theory of language perception, which relates the mental images of sound-producing gestures to the vocal apparatus [152]. Physical gestures can be mentally represented while listening to music, meaning that humans associate what they perceive and imagine to mental simulations of related events [97, 98]. For many centuries, people learned to listen to sounds that have a unique relation to the bodies that produced them. Indeed, the performers' body movements are closely connected to the mechanics of traditional instruments [122]. These schema are used both in the perception of familiar and unfamiliar sounds, because of the sound-gesture relationships present in the energy features of the sound (i.e. the overall envelop of the sound) [98].

Recent research in music cogntion has brought insights regarding the interactions between sound and action. Sound-tracing studies, where listeners are asked to draw the

Table 2.5 Figurative gestures

-Metaphorical -Perceived by the audience through sound -Are not necessarily associated to corporal actions of the performer -May be linked to structural features of the music [67]
-Related to a continuous process of sound-tracing -Are the result of a sound-gesture relationship present in the energy features of the sound [97, 98]

gesture shapes on a digital graphical tablet [94, 176] or using full-body motion capture [138], aim at measuring spontaneous rendering of melodies to movement. It appears that people use various gestural strategies to represent one particular sound [138]. For instance, the melodies with vibratos produce large changes in acceleration in participants' movements. Moreover, ascending pitch are traced as an ascending curve, and percussive onsets followed by a long decay are traced as an abrupt slope followed by a long descent [97].

2.2.4 Limitations of the taxonomy and further considerations for piano performance

Although researchers have found various ways to define the concept of gesture in music performance, it is particularly complex to know exactly what the nature of every movement is. Effective gestures are linked to musical events through a cause-and-effect relationship. Ancillary gestures help achieve a higher degree of control of the instrument and relates to the expressive character of a musical performance. Finally, figurative gestures are linked to how auditors translate the experience of listening to music in a mental experience. If the taxonomy provides a global view and solid conceptual framework, the boundary between certain categories, for instance effective and ancillary gestures, is difficult to trace, especially when considering each individual instrument. Since a specific gesture does not necessarily belongs to one strict category, it is essential to talk about a typology of gestural functions based on the instrument itself, and not simply a typology of gestures [24]. To exemplify the ambiguity between the different functional aspects of the typology of musical gestures in piano performance, we will discuss two types of body movements, namely finger and head movements.

First, finger movements, in addition to being in direct contact with the instrument, and thus understood as effective gestures, can also be considered as an indicator of personal expression. Dalla Bella and Palmer [56, 57] have shown that pianists' finger motion kinematics, found in attacks, keypresses, or at-rest position, can be considered as an indicator of personal identity and style and that it is possible to discriminate between different performers. Indeed, cognitive constraints and biomechanical factors, such as the degree of independence between fingers, can affect the range of possible movements. According to these constraints, pianists might use different movement strategies, yielding different sound outcomes, to achieve spatial and temporal accuracy.

Many physicists and acousticians claimed that the only essential factor in the control of the sound and timbre of the piano is the velocity at which the hammer hits against the strings [117, 216, 259]. However, in an early study conducted by Ortmann [178], it has been demonstrated that there exist different acceleration patterns and types of key control for both non-percussive (i.e. finger rests on the surface of the key before pressing it), and percussive touch (i.e. finger already moving strikes the key). The percussive touch (or struck touch) is characterized by precise control right at the moment of the impact, while with non-percussive touch (or pressed touch), the key depression needs to be controlled up to the very end. Therefore, the attack portion of the envelope affects the timbre, and is crucial in differentiating the types of touch used by a pianist. Repp [202] speculated that the type of touch a pianist uses influences the perception of timing and dynamics. Research conducted by Dalla Bella [57] and Goebl [104] corroborated this idea. Pianists' finger motion measurements were shown to influence the characteristics of the resulting sound, such as intensity of tones and timing precision, suggesting that finger movements typify pianists' originality and have an impact on their control of force and tempo. This suggests that the tactile-sensory information (i.e. key resistance, sound vibrations) from the keyboard is used by pianists in combination with the acoustic perception. Traube [240] also found that, when pianists incorporate more weight in their playing technique, they can feel the double escapement action of the piano, which has an impact on the piano tone. Results have shown that piano tones played with and without weight differ in terms of temporal and spectral features of the attack. Moreover, a study by Goebl and colleagues [102] has shown that musicians could identify the type of touch produced for an isolated piano tone, independently of hammer velocity.

Second, head movements, which are mainly associated to the expressive and personal language of the performer, have also been associated to acoustic changes in piano performance. Studies have demonstrated that even micro-movements of the head, which activate the vestibular system, plays a critical role in auditory encoding of rhythm. This suggests that the head motion may play an integral part in performers' rhythmic perception and sense of musical phrasing. A series of studies that aimed to understand how movement influences the auditory encoding of rhythmic information demonstrated that there was a multimodal interaction between auditory perception and movement [188, 189]. To indicate which aspects of the movement contribute to this interaction, Phillips-Silver and Trainor [190] tested for vestibular involvement by observing whether passive motion of the legs or head could guide or disturb the metrical interpretation of ambiguous rhythmic patterns. They found that the movements of the head only affected the auditory perception of duple or triple metrical structure. Their work also demonstrated that this effect could also be achieved without movements, through an artificial stimulation of the vestibular nerve [239].

These results imply that there could be a similar connection in music performance between the movements of the head and the performer's perception of the rhythm and phrasing.

In this thesis, we have made the choice of not using the term 'gesture' at all when talking about musicians' body movements and expression. We will rather use the following terms:

- **Movement/motion** will refer to the action of modifying the physical position of any parts of the body. This may be used in relation to any changes in amplitudes of motion.
- **Kinematic** will be used to describe the spatial details of the movement itself. Kinematics is not concerned with the internal or external forces that cause the movement [265]. Kinematic parameters include linear and angular displacements, velocities and accelerations.
- **Kinetic** will be used in relation the external forces that cause the movement. External forces come from the ground or external loads and must be measured by a force transducer (i.e. force plate). The kinetic variables comprise ground reaction force, center of pressure (COP), COP displacements and velocity of the COP displacement.

Finally, the last section will discuss different systems to capture real-time music performance data.

2.3 Realtime capture of musical performance data

Research focusing on musician-instrument interactions and musicians' movements analysis can benefit from recent technological advancements. Combining various data capture systems, such as motion capture, computer-controlled grand pianos, force plate, EMG and electronic sensors, can provide researchers with essential information about musicians' expression, posture and movements, as well as instrumental technique. These systems, which vary in terms of precision and accuracy, are discussed in this section to indicate how they are used in recent research on movements to capture real-time musical performance data, with a specific focus on piano-related studies. We will also report their respective advantages and limitations.

2.3.1 Motion capture systems

Several types of motion tracking and sensing technologies exist to measure position and orientation, generate animated characters through full-body motion capture on human or animals, navigate through a computer graphics virtual world, etc. [256]. This section focuses on infrared optical motion tracking systems, such as marker-based systems (active or passive markers) and markerless systems. Optical motion capture systems use computer vision, a method to acquire, analyze, and interpret digital images that are processed by software in order to track motion [157].

Marker-based optical motion capture systems

Marker-based motion capture systems allow the precise and accurate reconstruction of the whole body (limbs, joints, face), as well as the capture of fine and complex movements, such as finger motions. As the speed of capture can go up to 1000 frames per second, and more if using high-speed camera (up to 10000 frames per second), these systems are very reliable and provide accurate 3D data. However, they are expensive and require a careful and tedious setup and calibration, as well as extensive data extraction procedures [6]. Two types of marker-based systems exist: passive optical and active marker systems.

Passive optical systems Passive optical systems (e.g. Vicon, OptiTrack, and Qualisys systems) consist of an array of cameras, connected to a computer running specialized software, that identify passive markers. These systems measure the 3D position of passive reflective markers through triangulation [168]. The markers, that are easily identifiable through computer vision algorithms, are reflective spheres that come out of the background. Special suits with markers can be used, otherwise, markers have to be applied on subjects' clothing or body.

The Vicon and Qualisys system have been used in many studies on clarinetists' body movements [175, 230, 231, 252], on pianists' fingertip motions [57, 105, 106] and pianists' upper body movements [157, 232]. Moreover, these systems were useful in studies on music and synchronization [139], music cognition [236], dance gestures [172], and facial expression of singers [155]. Figure 2.3 shows an example of the motion capture setup used in Goebl and Palmer's study on the timing and force control of finger movements in expert pianists.

Passive markers can be easily occluded by the keys and crossing hands, as well as being uncomfortable for pianists, which can be a challenge when capturing precise micro-movements, such as pianists' finger motion. If a marker falls or becomes blocked by another object, the tracking will be inaccurate, and certain markers might not be recognized. Polynomial interpolation functions can still be used to fill the gaps in the trajectory of the occluded markers between two parts if the gap is not larger than the maximum frame gap previously set by the user. Moreover, as the accuracy of these systems is affected by changes of lighting and temperature, they are not easily portable [157]. That leads to a less ecological data collection situation, such as using digital pianos to capture piano performance. However, more and more systems are designed to be used in different environments (i.e. MRI, underwater, outdoor), thanks to their ability to measure marker positions with high accuracy and speed, active filtering for outdoor motion capture, water resistant or

Fig. 2.3 Motion capture setup and marker placement on the keyboard. Fifteen markers were placed on the piano keyboard and six infrared cameras were used. Figure from Goebl, W. and Palmer, C. "Temporal Control and Hand Movement Efficiency in Skilled Music Performance" in PLoS ONE, vol. 8, 1, 2013 (c) 2013 Goebl and Palmer. (Used under the terms of the CC BY license).

electromagnetically shielded cameras, and to the fact that it can simply be run off a laptop (e.g. Qualisys motion capture cameras).

Active marker systems Certain motion capture systems, such as Optotrak and Codamotion systems, use active markers and require power to transmit the data they measure, which means that each marker is connected with wires to a power source (or to the main computer) [157]. Although this can be obtrusive and inhibit the musical performance, these systems still have the capacity to detect and accurately measure markers even if they are occluded at certain moments in the capture. Such markers have been used [184, 186] to measure finger movement in clarinet performance. This system was appropriate in this case because the finger motions during clarinet performance are more restricted than during piano performance. Nevertheless, active markers were used in Goebl and Palmer [105] to investigate pianists' finger movements in simple duet melodies.

Markerless optical systems and 2D video-based systems

Optical motion tracking systems, such as Vicon and Qualisys have been shown to be reliable and precise enough to be used in music performance research. However, many researchers with a musical background may not be sufficiently experienced to manipulate such technological equipment. Markerless or 2D systems, however, are less expensive than optical systems, and usually require less investment in terms of setup and data processing. They rely on image processing techniques to identify subjects without the use of special suits or markers. The Microsoft Kinect system has a RGB video camera, an infrared laser emitter and an infrared camera [142]. It uses a depth-sensing camera projecting an array of structured infrared light points to reconstruct a 3D image of objects in front of the sensor. Its depth measurements augment with increasing distance from the camera.

The Kinect tracking accuracy was previously compared to other 3D optical systems, such as Optitrak [254], OptoTrack [229], Codamotion [4] and Vicon [36]. Measurement errors were often reported in these studies and were larger than for the optical tracking systems, such as the Vicon system. Nevertheless, researchers have found that Kinect systems can be adequate for evaluating movement quality and posture in specific contexts. For instance, it can provide anatomical landmark displacement and trunk angle data with a comparable precision as a Vicon 3D system [36]. Moreover, joint position data during reaching movements captured with the Kinect and passive motion capture system were compared [213]. The measurement error was not significant enough to exclude the possibility of analyzing upper-limb movement quality with sufficient precision and discriminate between subjects with Parkinson's disease and healthy subjects. Moreover, using a Kinect and body landmark identification from depth images, Hadjakos and colleagues [111] showed that this system can effectively track the position of pianists' head, shoulders and arms from above the keyboard.

The Kinect's reliability and accuracy were also compared to the 2D reference coordinates of Dartfish motion tracking software. Dartfish software uses digital video as input and can generate values for the location of markers in two dimensions. The Kinect was found less reliable than the Dartfish 2D video-based system and not suitable for assessing pianists' postural changes, as it often lost track of skeletal positions [9]. Nevertheless, the Kinect was better at tracking head and neck positions than changes in shoulder, elbow and wrist posture in y-axis coordinates, but was unprecise regarding the changes to vertical alignment of the spine. The accuracy and precision of the Dartfish 2D tracking and analysis system was also previously evaluated in comparison with the 3D Vicon system [73]. The Vicon system generated the moments using force plate data. The Dartfish marker data were combined with anthropometric data [see 265] to infer the ankle moment. The Dartfish tracking data were similar to the 3D mocap Vicon system in terms of joint angles and moments.

Similarly to Dartfish system, the open source system EyesWeb [27] integrates different sensor systems, such as infrared, color and black-and-white video cameras, electronics for the synchronization between two video cameras, and provides a modular visual interface to enable the user to customize programs to observe and extract various movement information through libraries. This system is portable and is designed principally for full body motion capture in music and dance, and supports input devices, such as motion capture systems, videocameras, Kinect, microphones and analog inputs. It was previously used for perceptual experiments [30], for tracking the position of finger movements [22] or for real-time analysis of expressive gestures in human full-body movement [29].

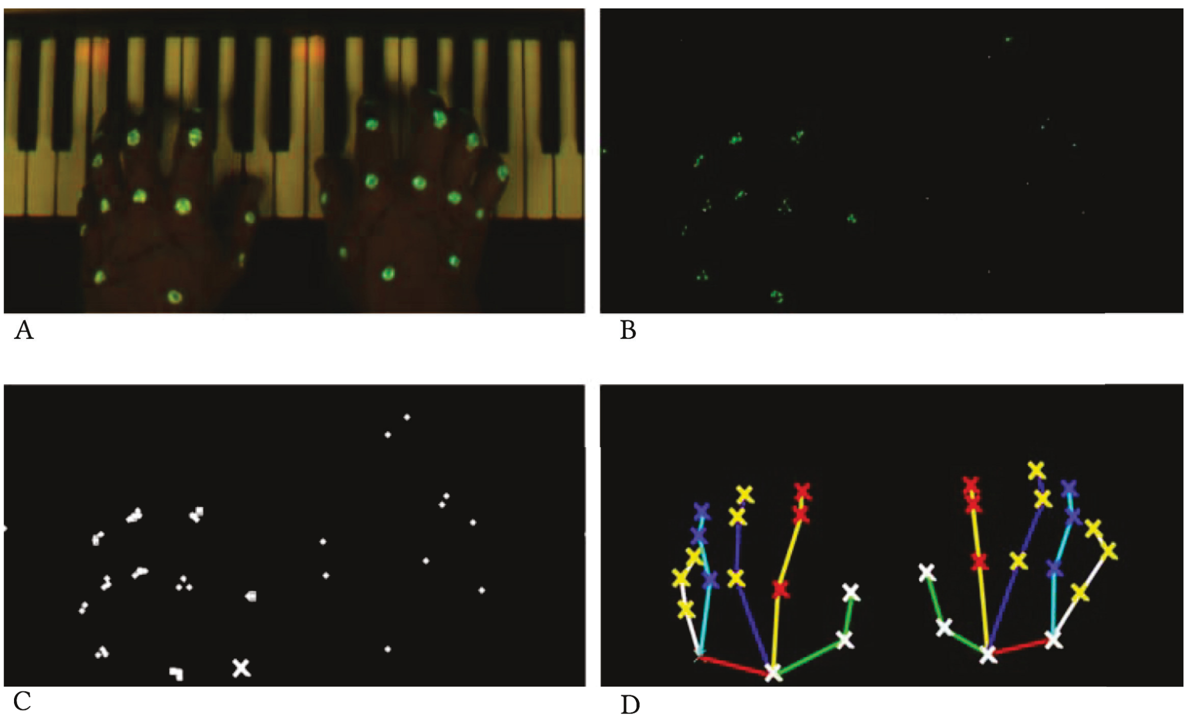

Fig. 2.4 Paint marker tracking with a blob detection algorithm. **A** Original image captured by the video camera; **B** the image is passed through a color filter; **C** Bloc detection result; **D** Final tracking results. Figure from MacRitchie, J. and Bailey, J. "Efficient Tracking of Pianists' Finger Movements" in Journal of New Music Research, vol. 42, 1, 2013 (c) 2015 Journal of New Music Research, Routledge. (Used with permission from the Journal of New Music Research).

MacRitchie and Bailey [157] have designed a low-cost and effective system to capture the movements of pianists' fingers (Figure 2.4). They combined image processing systems with high frame rate cameras. Their system measures the position of each part of the finger with passive paint markers and image processing techniques. In addition to being unobtrusive for performers, the system may be used in any environment (e.g. concert halls, laboratories, or practice rooms), as long as the lighting can be controlled. Although occlusion may occur in passages where fingering patterns require the thumb to go under the hand, the system can still manage to estimate the position of occluded markers by calculating the average position between each frame.

Certain limitations should be acknowledged with markerless and 2D video-based systems, such as a potential inaccurate calibration due to the sensor and lighting condition, or again the obstruction of the measurement if reflective surfaces are overexposed in the infrared image [142]. In addition, the rate of capture of most markerless systems are influenced by the technical characteristics of the cameras used. The Kinect and Dartfish systems might not be really appropriate for fast finger movements at the piano but can still provide a precise low-cost solution for tracking macro body movements. However, image processing systems, such as the paint marker mocap system, may be a good compromise between the precision of very expensive and static technologies, such as 3D motion capture systems, and other technologies that may not be accurate enough to track fast and precise movements.

2.3.2 Grand piano-embedded CEUS digital recording system

Grand piano-embedded CEUS digital recording systems are useful devices to measure various expressive parameters, such as tone onsets and offsets, final hammer velocity, and the movements of the pedals [101]. Two systems are commonly used in piano performance research: the Yamaha Disklavier [15, 185, 200, 234] and the Bösendorfer SE system [15, 100, 182, 260]. Computer-controlled grand pianos are augmented with optical sensors behind the keys, hammers, and pedals, and microprocessors and electronic boards that measure the time intervals between key strikes (also referred to as inter-onset intervals), the velocity of each strike, and the duration with which each key is held down. Those types of piano allow the measurement and reproduction of the piano behavior, including the movements and speed of the hammers, thanks to solenoids attached to each key [11, 12]. Bernays and Traube [11, 12] have developed a MATLAB toolbox for studying and visualizing various characteristics of piano touch and acoustic nuances, such as articulation, timing, dynamics, attack, timbre, and pedaling. The toolbox allows for a quantitative analysis of expressive features and their gestural control through chords and notes selection tools, score-performance matching, and automated statistical analyses. Each note can be characterized by 46 features, such as onset, offset, duration, maximum hammer velocity, maximum key depression angle, and their associated timestamps, sustain and soft pedals use, as well as their duration of use and amount of depression. On the Disklavier, the data are stored in standard MIDI format, and in a special file format for the Bösendorfer.[1]

2.3.3 Force plate

Force plates have been used in human movement analysis to measure different parameters, such as ground reaction forces, centre of pressure (COP) and derived kinetic variables [170], and to analyze gait and balance (e.g. [31, 43, 50, 207, 263]). Force plates were also used in biomechanical studies to compare different methods to estimate the center of mass [10, 149, 269]. In music performance, Rozé [210] used it to measure the impact of different movement conditions on cellists' postures in terms of the COP area and orientation.

A force plate includes force transducers that measure an electrical signal proportional to the applied force. There exist different kinds of force transducers: strain gauge load transducers [242], piezoelectric devices [221], capacitive ones, etc. It was shown that strain gauges have advantages over piezoelectric sensors in terms of stability for long-term mea-

[1] Each recording includes a set of three files with the extensions ".kb" for keyboard information; ".lp" for the loud pedal; and finally ".sp" for the soft pedal. The CEUS ".boe" format is converted to the MIDI format and is therefore available for local network-capable MIDI connections.

surements [208]. Force transducers are placed in the four corners of the force plate and calculate the resultant force acting on the plate. A Calibration matrix, with six diagonal values, is used to calibrate the force plate. The force vector is three-dimensional and shows the acting force, namely the vertical component and the medial-lateral and anterior-posterior forces [253].

2.3.4 Electromyography (EMG)

EMG is a technique that records the electrical activity of skeletal muscles [206]. Given that the most commonly reported medical problems in musicians reside in muscle and tendons injuries [14, 70, 83, 114, 204], EMG can be useful to understand better musicians' used of upper-limb movements and discern the potential causes of musculoskeletal disorders.

The kinematic, kinetic and muscular activity of pianists' upper-limb movements has been studied over the last few years in order to understand better the organization of multi-joint movements during fine motor actions, with position sensor cameras, EMG system and inverse dynamic technique. A difference between expert and novice pianists was observed during elbow extension muscular torque for piano key striking [84]. Moreover, the effect of tempo and the interaction between loudness and tempo on muscular activities of the upper extremity was also examined [81, 82]. Results showed that the velocity of the shoulder, wrist and finger, as well as the triceps muscle activity increase with tempo and with louder tones, whereas the elbow velocity decreases. To understand how the upper-limb movements differ between the pressed and struck touches, Furuya and colleagues [80] focused on the muscle activities and kinematics in key-depressing motion. It was found that, to compensate for the small elbow velocity when a pressed touch is used to play the desired loudness of tone, pianists use larger shoulder and finger flexion velocity, induced by wrist and elbow muscular contraction.

2.3.5 Electronic sensors

Electronic sensors can be easily integrated into instrumental lessons due to their portability. For instance, accelerometer and gyroscope sensors were attached to the arm of a pianist to distinguish between various piano playing patterns, tremolos, scales, jumps and repetitions of octaves [112]. The data obtained were angular velocities and acceleration from movement of the arm, passive arm motion from finger forces, and motion of the sensor due to inertia.

Accelerometers are cheaper altogether than a passive marker system, but still many problems can occur during a measurement session, such as drift and potential gaps [157]. In order to measure individual parts of finger movement, one requires multiple devices connected through wires to a computer or a power source. This may lead to disturbance of the musician's performance. Accelerometers can be used in combination with mocap systems to measure position and orientation of objects or body parts more accurately [215]. The mocap system can be used to calibrate the accelerometer and remove the gravity component from the accelerometer signal, which is particularly sensitive to gravity and inclination [196].

Electronic sensors can also be integrated in acoustic instruments to capture data outside of the laboratory environment. For instance, a keyboard interface was created by McPherson and Kim [167], based on a modified Moog Piano Bar, with optical reflectance sensors placed on the white keys, and interruption sensors on the black keys. On this interface, LEDs and photodiodes are mounted above each key to calculate how much light is reflected off the key surface. The system was then used in McPherson and Kim [166] to capture distinct gestural dimensions, such as velocity, percussiveness, weight, rigidity of fingers and depth. McPherson [165] also developed a technology based on capacitive touch sensors fixed on the surface of each piano key. These sensors measure the XY location and contact area on the keys without any pressure needed to activate the sensor. In MacRitchie and McPherson [158], the sensors were combined with a monocular image-processing based system that track colored markers with a single RGB camera and an infrared MIDI sensor placed at the back of the keys. Figure 2.5 shows the TouchKeys capacitive touch sensors and the setup of the experiment. The devices collected data on the location of the markers and touch events simultaneously.

A B

Fig. 2.5 **A** TouchKeys capacitive touch sensors on the keys of a Yamaha C5 grand piano. **B** Setup of the sensors (monocular high-speed camera, Moog PianoBar (back of the keyboard), and TouchKeys sensors (right picture) (Figure from MacRitchie, J. and McPherson, A.P. "Integrating Optical Finger Motion Tracking with Surface Touch Events" in Frontiers in Psychology, vol. 6, 702, 2015 (c) 2015 MacRitchie and McPherson. (Used under the terms of the CC BY license).

Researchers also have looked into kinematics and kinetics of key movements while pianists played different types of touches (pressed or struck) at various sound levels [103, 144], using computer-controlled pianos and accelerometers or strain-gauge force transducers attached to the keys. Results revealed that the pressed touch was characterized by a less abrupt initial force, and a travel time considerably longer than the struck touch, indicating precise control of finger-tip movements, intensity and tone onset.

In this thesis, Qualisys motion capture system was combined with Bertec force plate technology to study pianists' body movements and posture in relation to expression and structural parameters of pieces from the Romantic repertoire. In addition, we recorded MIDI data from the piano keyboard and video and audio recorded the experiments. The synchronization protocol used can be found in Appendix A. The Plug-in-Gait marker model and the setup of the mocap cameras an force plate can be visualized in Appendix B. The three Romantic excerpts used throughout the research are listed in Appendix C. Finally, the questionnaires and task instructions, as well as participants' answers, can be found in Appendix D.

Chapter 3

Exploratory Study

The main objective of this exploratory study is to identify the relationships between pianists' use of motion cues (i.e. quantity of motion (QoM) and force applied on the stool) and acoustic parameters that convey expression and information about the structural parameters of music. The specific questions addressed are the following:

1. How individual pianists modulate their movements according to different performance conditions when playing a piece of their choice?
2. What regions of the score with expressive conditions have an impact on the body movements?
3. Are musically trained auditors better at recognizing different performance conditions in Romantic piano pieces when provided with one perceptual mode at a time (visual or auditory) or both?

The results from this exploratory study helped better understand the influence of different pieces and pianists on the variations of body movements and audience perception, as well as determine the methodologies to be adopted in the subsequent studies.

3.1 Experimental method

This exploratory study is divided into two parts: 1) a quantitative analysis of pianists' physical data, and 2) a perceptual test conducted with musically trained auditors.

3.1.1 Participants and musical tasks

Participants

Eleven pianists (3 undergraduate, 2 master, 6 doctorate, and 1 postgraduate students, 4 females and 7 males) participated in the exploratory study.

Thirty auditors (average of 24.3 years old, SD=5.7, 15 females and 15 males), with at least 5 years of musical training, participated in the perceptual part. Twenty-one were undergraduate students and 9 were master or doctorate students. All participants signed a consent form approved by the University ethics committee.

Choices of excerpts

Each pianist played a different thirty-second excerpt from their respective Romantic repertoire. Romantic excerpts were chosen for the expressive characteristics of this style. Indeed, it was shown that the compositions of the Romantic period until Post-romanticism diverge more and more from the principles of the tonality [21] and are rhythmically more variable [58]. The following excerpts were performed:

- **Pianist 1** Chopin 4th Ballade (mes. 152-160)
- **Pianist 2** Brahms 3rd Piano Sonata (Trio) (mes. 58-105)
- **Pianist 3** Chopin scherzo No. 2 (mes. 1-50)
- **Pianist 4** Schumann Fantasy (mes. 1-19)

- **Pianist 5** Liszt 2nd Ballade (mes. 225-234)
- **Pianist 6** Medtner Sonata Reminiscenza Op. 38 (mes. 253-274)
- **Pianist 7** Listz Spanish Rhapsody (Andante moderato) (mes. 17-41)
- **Pianist 8** Chopin Waltz Op. 64 No. 2 (mes. 17-48)
- **Pianist 9** Schubert Impromptu No. 2 (mes. 1-25)
- **Pianist 10** Brahms Capriccio Op. 76 No. 1 (mes. 14-27)
- **Pianist 11** Chopin Impromptu (mes. 43-51)

Each excerpt was performed in four different conditions in the same order for all pianists: normal, deadpan, exaggerated, and immobile. The normal performances were played as naturally as possible. Deadpan referred to playing with a reduced level of expression, whereas exaggerated consisted in playing with an exaggerated level of expression. To perform the immobile condition, pianists were asked to restrict their movements to the essential ones to produce an acceptable performance, as close as possible to a natural expressive sound. Pianists repeated their excerpt three times for each expressive condition (total of 12 performances per pianist). Participants could choose the tempo they thought was appropriate to convey the expressive conditions.

The diversity of repertoire allows us to make various relationships between the compositional structure and the pianists' gestural language. The fact that pianists could play an excerpt of their choice allowed them to be comfortable with a piece they had practiced for a certain time and which technical level was adapted to their respective expertise.

3.1.2 Procedure

Pianists' measurements

Pianists' performances were video recorded with a Sony PMW-EX3 Wide Angle video camera and audio recorded with a Sennheiser MKH-8040 microphone. Motion data were collected, at a rate of 240 frames per second, with a 10-camera Qualisys motion capture system (referred later as mocap), using 49 passive reflective markers put on the pianists' hands, elbows, shoulders, torso, head, and pelvis. Force applied on the stool was measured with a force plate positioned under it (Bertec FP-4060 force plate). The beginning of each frame was time-stamped (SMPTE timecode) at 25 Hz, and a Rosendahl Nanosyncs HD word clock, sampled at 48 kHz, generated the clock signals for all the digital devices. The Rosendahl Nanosyncs was connected to the video camera, the Qualisys Sync Unit, and the RME Fireface audio interface. The Qualisys Sync Unit converted the SMPTE signals so that it may be recorded by the mocap cameras. The audio recording was slaved to the video signal.

Perceptual test

Auditors were randomly assigned to a modality (vision, audio, or both) and were asked to discriminate the expressive conditions and associate them to the appropriate performances. They could listen to the excerpts as many times as they wanted to in order to associate the musical excerpts to the expressive conditions. After each trial, auditors selected a confidence level on a five-point Likert scale for their answer. Auditors filled out a demographic questionnaire at the end of the experiment.

3.2 Results

3.2.1 Physical measurements

To obtain a global portrait of the differences between the conditions, we averaged the total QoM of all the body parts of interest (head, torso, both shoulders, both arms, both hands, and hips), as well as the cumulative sum for the force data.

Total QoM and force

Table 3.1 shows the resulting absolute difference of QoM and force, with their respective percentages, between the deadpan, exaggerated and immobile conditions and the normal one. Pianist 11's QoM obtained in the exaggerated and immobile conditions vary more from the normal condition than any other pianists' performances, with a decrease of 81.77% for the immobile condition and an increase of 32.66% for the exaggerated condition. The largest variation in QoM between the deadpan and normal conditions is observed in pianist 6's performances, with a difference of 60.35%. Pianist 1's performances demonstrate less variation between the deadpan and immobile conditions, with a difference of respectively 8.48% and 13.93%. The variations in force between the deadpan and normal conditions, as well as between the immobile and normal conditions are the largest for pianist 6's performances, with a difference of 93.90% for the deadpan condition, and 81.20% for the immobile condition.

Structural parameters

This section discusses the regions in the score where the conditions affect the movements of the head and the force applied on the stool. While certain pianists' movements differed significantly between the exaggerated, immobile or deadpan conditions and the normal

Table 3.1 Average total QoM (mm) for all body parts, force (N) and absolute difference between the normal condition and each other condition.

	Performance condition	QoM (mm)	% Difference	Force (N)	% Difference
Pianist 1 - Chopin 4th Ballade	Normal	1343.54		17259.19	
	Deadpan	1234.25	-8.48	16939.97	-1.87
	Exaggerated	*1718.14*	*+24.47*	*21536.57*	*+22.05*
	Immobile	**1168.62**	**-13.93**	**16457.95**	**-4.75**
Pianist 2 - Brahms 3rd Piano Sonata	Normal	2337.19		33530.10	
	Deadpan	**1317.30**	**-55.82**	**19148.47**	**-54.60**
	Exaggerated	*2765.23*	*+16.78*	*41145.72*	*+20.40*
	Immobile	1587.73	-38.19	28431.79	-16.46
Pianist 3 - Chopin scherzo No.2	Normal	2669.42		32375.74	
	Deadpan	**1894.91**	**-33.94**	**21075.74**	**-42.28**
	Exaggerated	*3181.57*	*+17.51*	*37439.05*	*+14.50*
	Immobile	2015.76	-27.90	27411.16	-16.61
Pianist 4 - Schumann Fantasy	Normal	1465.11		22140.80	
	Deadpan	1208.62	-19.19	23324.26	+5.21
	Exaggerated	*1702.11*	*+14.97*	*33052.49*	*+39.54*
	Immobile	**932.92**	**-44.39**	**18326.71**	**-18.85**
Pianist 5 - Liszt 2nd Ballade	Normal	2003.60		23182.54	
	Deadpan	1521.30	-27.37	22970.64	-0.92
	Exaggerated	*2009.21*	*+0.28*	*26475.57*	*+13.26*
	Immobile	**1349.44**	**-39.02**	**17737.60**	**-26.61**
Pianist 6 - Medtner Sonata Reminiscenza Op.38	Normal	4066.41		70662.58	
	Deadpan	**2181.23**	**-60.35**	**25509.48**	**-93.90**
	Exaggerated	*4155.35*	*+2.16*	*95840.73*	*+30.24*
	Immobile	2426.48	-50.51	29854.80	-81.20
Pianist 7 - Listz Spanish Rhapsody	Normal	3708.63		69078.96	
	Deadpan	**2350.05**	**-44.85**	40827.15	-51.41
	Exaggerated	*3856.48*	*+3.91*	*71882.23*	*+3.98*
	Immobile	2566.19	-36.41	**39017.96**	**-55.62**
Pianist 8 - Chopin Waltz Op.64 No.2	Normal	2262.21		38197.70	
	Deadpan	1910.91	-16.84	37059.73	-3.02
	Exaggerated	*2466.09*	*+8.62*	*42965.94*	*+11.75*
	Immobile	**1659.94**	**-30.71**	**33501.18**	**-13.10**
Pianist 9 - Schubert Impromptu No. 2	Normal	746.62		22511.55	
	Deadpan	659.90	-12.33	20989.28	-7.00
	Exaggerated	*972.70*	*+26.30*	*24491.95*	*+8.43*
	Immobile	**616.27**	**-19.13**	**19981.28**	**-11.91**
Pianist 10 - Brahms Cappriccio Op.76 No. 1	Normal	1854.82		17459.08	
	Deadpan	974.06	-62.27	14834.97	-16.25
	Exaggerated	*1987.76*	*+6.92*	*23321.84*	*+28.75*
	Immobile	**960.29**	**-63.55**	**13522.39**	**-25.41**
Pianist 11 - Chopin Impromptu	Normal	1230.77		11350.50	
	Deadpan	720.23	-52.34	11317.08	-0.29
	Exaggerated	*1711.18*	*+32.66*	*13424.47*	*+16.74*
	Immobile	**516.41**	**-81.77**	**10551.59**	**-7.30**

condition, others' movements did not show the same level of variance. To illustrate the relationships between the movements and the musical structure, we consider the pianists who present a significant difference in terms of QoM and force applied on the stool between the performance conditions, namely pianists 1, 6 and 11.

Figure 3.1 shows pianist 11's head position data in the x-axis in the four different conditions. Pianist 11's excerpt is characterized by a peaceful and slow rhythm, and smooth dynamics and articulation. The movement is significantly reduced in the immobile and deadpan conditions as compared to the normal condition and amplified in the exaggerated performance condition only in certain regions of the score. At 10 s the head starts moving in the opposite direction (i.e. toward the left side of the keyboard), and around 14 s, the head changes direction abruptly to demarcate the return of the main theme in the exaggerated condition.

Figure 3.2 shows pianist 1's head position data on the x-axis while performing an excerpt of the Chopin's 4th Ballade. Table 3.1 showed that pianist 1's total QoM varies the least between the deadpan and normal conditions, and between the immobile and normal conditions as compared to other pianists. The ternary rhythm at the left hand is constant throughout the excerpt and is composed of sixteenth notes grouped in two segments for each measure. The variance is greater in the exaggerated condition at 14 s (region A) and 21 s (region B), which respectively correspond to the return of the main theme, and to a big interval in the melody. The head movement is highly periodic, following the constant rhythm at the left hand, even in the immobile condition. The head motion in the immobile condition also highlights the return of the theme at 14 s.

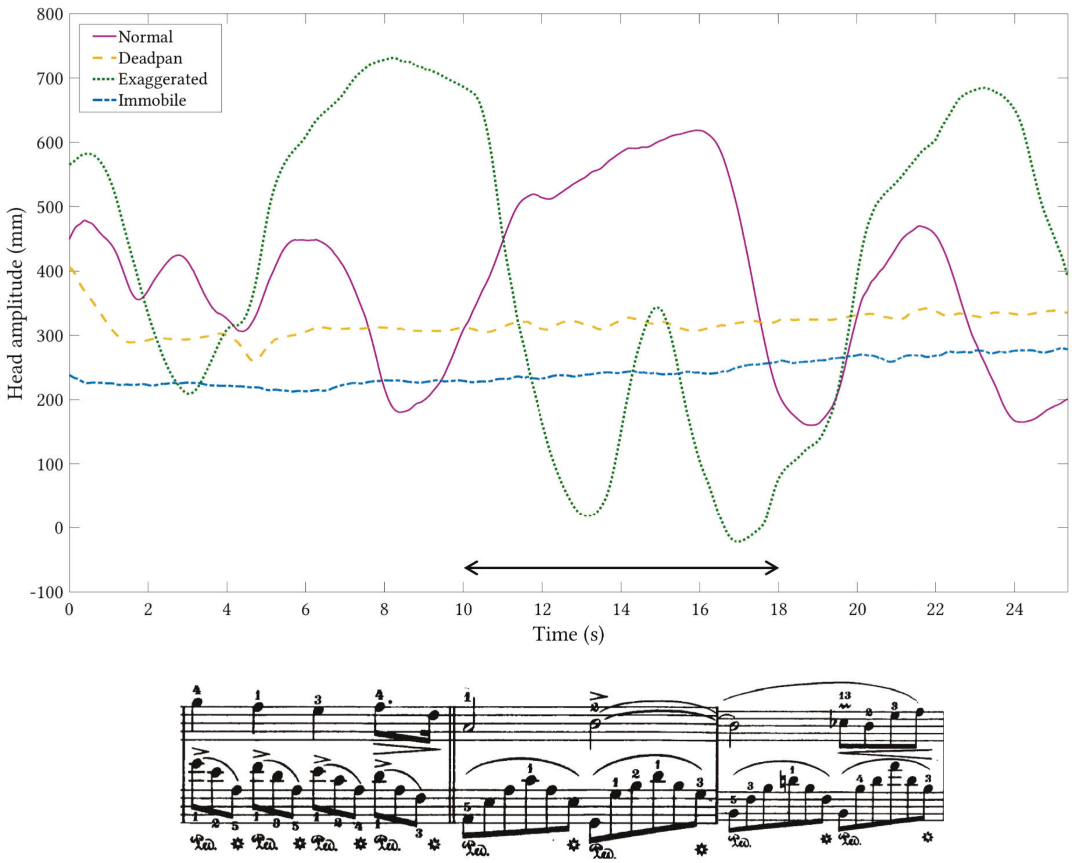

Fig. 3.1 Pianist 11's time-series of the head position data on the x-axis (along the keyboard) for the Chopin Impromptu in the four conditions.

It is interesting to note the large variations in force during pianist 6's deadpan and immobile performances. Pianist 6's excerpt presents a high dynamic level, large chords in the low register, and a staccato articulation. Figure 3.3 compares the normal and immobile conditions in terms of the force applied on the stool. Although the use of force is considerably reduced in the immobile condition, two moments in the performance (regions A and B) still share similar patterns of force with the normal condition. The first one corresponds to a series of accentuated dominant chords with forte dynamic (between 21 s and 25 s), and the second one occurs at the climax of the piece (at 33.5 s).

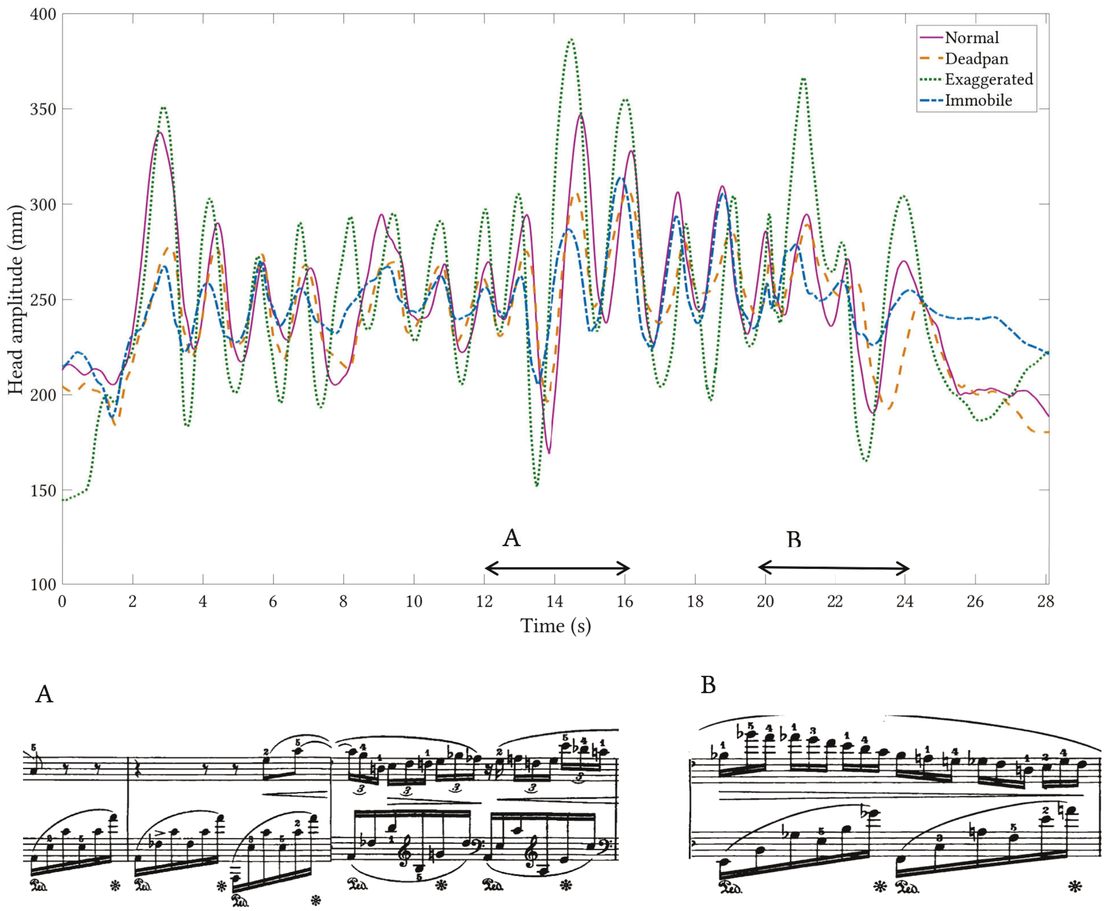

Fig. 3.2 Pianist 1's time-series of the head position data on the x-axis (along the keyboard) for the Chopin 4th Ballade in the four conditions. Regions A and B correspond to two passages with large deviations in amplitude of motion during the exaggerated condition.

3.2.2 Perceptual test

To examine the effect of the different expressive conditions, the modalities, and individual pianists on the auditors' ability to discriminate the excerpts, an analysis of variance (ANOVA) with repeated measures was conducted for each of the dependent variables, with the auditors' gender, instruments and level of instruction treated as the random variables, and the pianist, modality, and condition treated as the fixed variables. A significant main

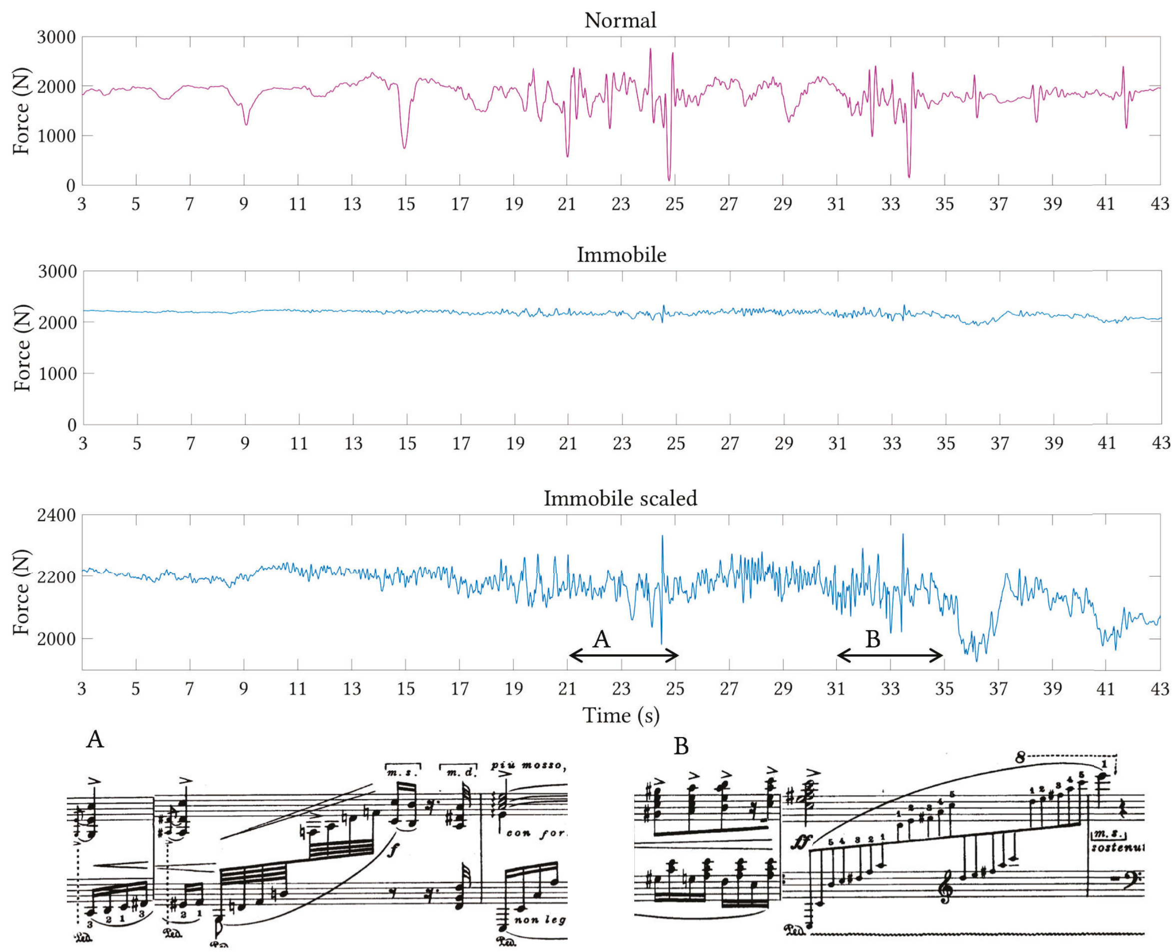

Fig. 3.3 Pianist 6's time-series of the force data for the Medtner Sonata Reminiscenza. The two first graphs show the normal and immobile conditions with the same scale ranges and the third graph shows the adjusted scale for the immobile condition. Regions A and B correspond to two passages with similar patterns of force in both the normal and immobile conditions.

effect was found for the conditions [$F(3, 1231) = 6.6$, $p < .01$] on auditors' answers, but not for the modalities. Additionally, there is a significant interaction effect between modalities and conditions [$F(6,1231) = 5.9$, $p < .01$]; between the modalities and the pianists [$F(20,1231) = 2.5$, $p < .01$]; and between the conditions and the pianists [$F(30, 1231) = 1.9$, $p < .01$]. No significant effect is observed for the auditors' instrument, gender or instruction level. In other words, auditors who are pianists do not perform better at the task than other instrumentalists.

Figure 3.4 compares the results obtained for the modalities in each condition. Overall, all the conditions are better identified in the audio-visual modality (M=76.1% of good answers; SD=11.7), followed by the visual-only modality (M=72.5%; SD=5.8), and finally the audio-only modality (M=65.5%; SD=11.4).

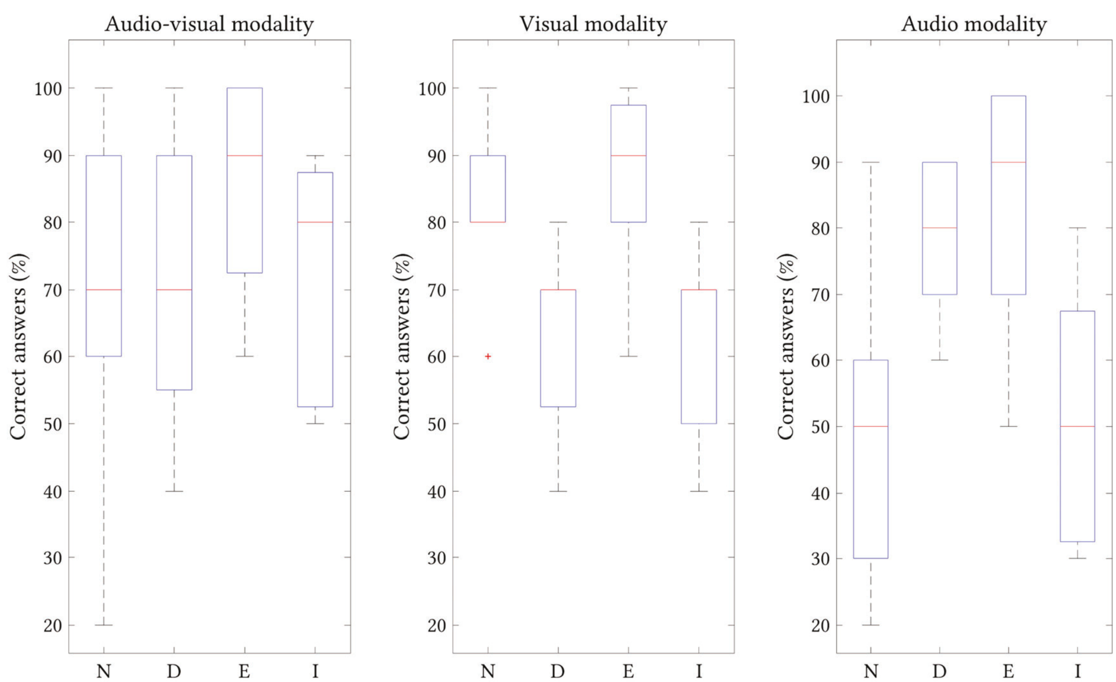

Fig. 3.4 Distribution of the median values per modality illustrating auditors' correct answers with respect to the conditions (N: normal; D: deadpan; E: exaggerated; I: immobile)

The exaggerated performances are fairly well recognized in every modality (*Mdn*=90%). The identification of the normal condition in the audio-visual mode varies considerably from 20% to 100% of good answers and is better recognized in the visual-only mode (*Mdn*=80%). Answers vary between auditors for the normal condition in the audio-visual mode (*SD*=11.7) and the audio-only mode (*SD*=11.4), but less for the visual-only mode (*SD*=5.8). The auditors' level of confidence in identifying the conditions is higher in the audio-visual modality (weighted average=78.9%) than in the visual-only mode (weighted average=73.5%) and in the audio-only mode (weighted average=66.8%).

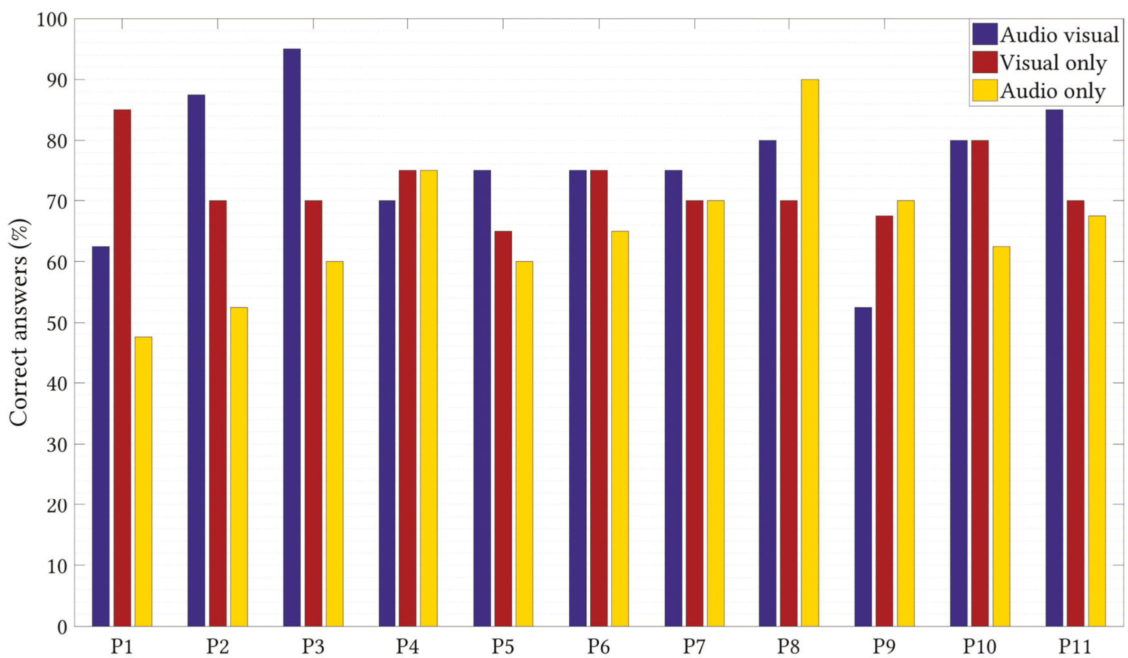

Fig. 3.5 Percentage of auditors' correct responses per pianist for each modality

Figure 3.5 shows that the auditors' identification of the expressive conditions varies greatly with the modality when different pianists perform. For instance, the conditions are better discriminated in the audio modality than in the audio-visual mode for pianists 4, 8, and 9. However, they are better recognized in the audio-visual mode, followed by the visual-only and the audio-only modes for pianists 2, 3, 5, and 11. Overall, auditors are better at identifying the conditions when pianists 3 and 8 are playing, with an average of 75% and 80% of total good answers respectively, and the lowest average score during pianist 9 playing (63.3% of good answers). Interestingly, the conditions in the audio-only modality for pianist 8 are well recognized with 90% of correct answers. For pianists 6 and 10, auditors were equally able to associate the performances to the correct conditions in the audio-visual and visual-only modalities.

3.3 Discussion and justification for the choice of excerpts

Choice of excerpts for Chapters 4 and 6 In this exploratory study, a quantitative analysis was realized on movement data showing interesting comparative results between the compositional structure and the pianists' gestural language for three of the 11 pieces, namely the Sonata Reminiscenza, the Chopin 4th Ballade and the Chopin Impromptu. These three pieces diverge the most in terms of QoM and force for the deadpan, exaggerated and immobile conditions.

For the Sonata, large variations in QoM in the deadpan and immobile performances were observed as compared to the normal condition, but the excerpt was played with similar QoM for the normal and exaggerated conditions. The largest variations in force between the normal, deadpan and immobile conditions were noticed for that excerpt, which is surprising considering the very dynamic and changing character of that excerpt, with many ascending movements and accentuated chords, long arpeggios, varied rhythm and chromatic passages.

We found the smallest variations in QoM between the normal, deadpan, and immobile conditions for the pianist who performed the Ballade. That excerpt presents a polyrhythm between both hands (i.e. constant ternary rhythm at the left hand against a rhythmically unstable melody at the right hand). Head movements were also periodic, following the rhythm at the left hand, even during the immobile performance.

The largest differences in QoM between the conditions were observed for the pianist who played the Impromptu. Indeed, the deadpan and immobile conditions were performed with almost no variations in amplitude of head movement. The slow and regular rhythm, the smooth dynamics and articulations, and the rubatos accompanying the phrase and section boundaries probably allow the pianist to move more freely.

Our results showed that the head QoM is an important motion cue used by pianists to convey different levels of expression, as found by Davidson [60] and Thompson and Luck [232]. It is important to note that the excerpts did not present the same level of technical difficulty. For instance, the complexity of pianist 1's excerpt, the Ballade, is reflected in an impetuous rhythm at both hands and many chromatic passages. Therefore, that particular excerpt probably gave fewer opportunities to change significantly the movements across conditions.

Because the Medtner Sonata Reminiscenza, the Chopin 4th Ballade and the Chopin Impromptu present characteristic technical challenges, for chapters 4 and 6, we based our quantitative analysis on those pieces to investigate the impact of technically different excerpts of the Romantic era on expert pianists' use of timing, QoM, postural angles, as well as kinetic parameters (force).

Choice of excerpts for Chapter 5 This exploratory study showed that auditors were able to differentiate pianists' different expressive performances in the three modalities, as Juchniewicz [132] demonstrated, but were better in the audio-visual modality, which diverges from Davidson's results [60], who used the point-light technique. Nevertheless, in the audio-only modality, the normal and immobile conditions were not easily discriminated from one another as shown by the lower level of auditors' good answer results. Auditors were also often confused between the deadpan and immobile conditions in the visual-only mode. This might be explained by the fact that, even though no instruction was specifically given to pianists with regard to the level of movement in that particular condition, the deadpan condition was performed with a reduced level of motion. Playing in a deadpan manner may naturally restrict the movements, which may, in turn, suggest that movements are intrinsically connected to expression of pianists. Similar results were also found for the normal and immobile performances in the audio-only modality, meaning that pianists played with a normal expression while restricting their movements. This supports Nusseck and Wanderley's findings [175], which pointed out that removing certain kinematic features from the performance might not entail changes in auditors' audio perception of acoustic parameters. Additionally, the responses for the normal condition in the audio-visual mode varied considerably from 20% to 100% of good answers. This suggests that the removal of auditory information might help discriminate certain conditions.

Auditors were better at discriminating the conditions in the visual mode for pianist 1 who performed the Ballade but also obtained the lowest scores in the audio mode. For pianist 6 who played the Sonata, auditors obtained the average results for each modality, which provides a good comparison point. These results suggest that there is either an effect of the pianist or the excerpt which allows listeners to discriminate correctly the performances in one particular modality.

In order to understand whether this effect was attributed to the pianist's performance or the excerpt itself, we decided to specifically compare two of the pieces from this preliminary study: the Medtner Sonata Reminiscenza and the Chopin 4th Ballade. These pieces were chosen because we were interested in the influence of body movements on auditor perception and their ability to discriminate between performances. Indeed, they present 1) technical difficulties, contrasting characters and structural features, and showed 2) distinctive perceptual data results in this exploratory study.

Chapter 4

Kinematic Analysis of Pianists' Expressive Performances of Romantic Excerpts: Applications for Enhanced Pedagogical Approaches

The following chapter was published in:

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Abstract

Established pedagogical theories for classical piano usually do not consider the essential relationship between the musical structure, whole body movements, and expression. Research focusing on musicians' expression has shown that body movements reflect the performer's understanding of the musical structure. However, most studies to date focus on the performance of a single piece at a time, leaving unanswered the question on how structural parameters of pieces with varied technical difficulties influence pianists' movements. In this study, ten pianists performed three contrasting Romantic excerpts in terms of technical level and character, while motion data was collected with a passive infrared motion capture system. We observed how pianists modulate their performances for each of the three pieces and measured the absolute difference in percentage of duration and quantity of motion (QoM) between four expressive conditions (normal, deadpan, exaggerated, immobile). We analyzed common patterns within the time-series of position data to investigate whether pianists embody musical structure in similar ways. A survey was filled in by pianists to understand how they conceive the relationship between body movements and musical structure. Results show that the variation in duration between the exaggerated and deadpan conditions was significant in one measure for one of the excerpts, and that tempo was less affected by the QoM used than by the level of expression. By applying PCA on the pianists' position data, we found that the head QoM is an important parameter for communicating different expressions and structural features. Significant variations in head QoM were found in the immobile and deadpan conditions if compared to the normal condition, only in specific regions of the score. Recurrent head movements occurred along with certain structural parameters for two of the excerpts only. Altogether, these results indicate that the analysis of pianists' body movements and expressive intentions should be carried out in relation to

the specific musical context, being dependent on the technical level of the pieces and the repertoire. These results, combined with piano teaching methods, may lead to the development of new approaches in instrumental lessons to help students make independent choices regarding body movements and expression.

4.1 Introduction

While it is common knowledge that musicians' body movements contribute to the audience's understanding of the musical score and the performer's expressive interpretation of music [54, 247, 255], the teacher rarely explicitly guides the students to connect their movements to the structural and stylistic features of a piece [135, 137, 268]. Although previous research has been conducted on musicians' expressive communication, the impact of the structural parameters of technically challenging pieces on pianists' body movements and expressive parameters remains largely unexplored. The majority of piano pedagogical theories are centered on fingering technique and on the position and weight of the hands and forearms (e.g. [148, 151, 258]). Piano teaching would benefit from the inclusion of a science-based pedagogical perspective by incorporating the results of recent experimental studies. A kinematic analysis of experienced pianists' body movements and musical timing in relation to the structural elements from various pieces of music would bring invaluable information that may help student performers monitor their body movements to improve their expressive communication abilities while consistently manipulating acoustical and physical parameters. These results can contribute to the design of a coherent pedagogical framework that may impact piano pedagogy.

In the literature on music performance, two types of gestures have received more attention: effective or instrumental gestures, and sound-accompanying or ancillary gestures

[25, 68, 251]. Effective gestures are responsible for the direct control of the quality of the sound and changes applied to the instrument itself, while ancillary gestures are not necessarily related to sound production and are mainly the result of three factors: ergonomic, structural and interpretative. The latter are responsible for postural adjustments and they help stabilize the performance, anticipate movements, and maintain the tempo [98, 128]. They reflect the performer's individual representation of the music, which is affected by psychological and emotional states. To understand better the functions of body motion in relation to sound, researchers have discussed these different types of gestures, occurring on different timescales, as coarticulated actions [95, 96, 128]. For instance, a scale played on the piano might seem like a series of separate actions, when considering the finger movements only but those movements are connected and perceived as one coherent gesture if we concentrate also on the movements of the hand, arm, and upper body. In other words, the movements of the whole body may have a perceptual impact on expressive parameters. A recent embodied music cognition theory addresses the close relationships between the musician, his/her body movements and musical instrument, stating that the instrument is a natural extension of the musician's body [174]. The musician's body is described as an intermediary between the physical environment and one's personal musical experience [150]. The whole-body movements may be so ingrained in a pianist's technique that removing or attenuating some of them may be detrimental to the sound result.

In piano pedagogy, arms and hands are often at the heart of learning the instrumental technique. This approach, although motivated by virtuosity achievement, does not integrate other types of body movements, which coexist with the gestures involved in the production of the sound. To investigate how body movements are connected to musical expression and structural parameters, previous studies used different experimental conditions with gradual levels of expression. [60, 61] asked violinists and pianists to perform in three conditions denoted as deadpan, projected and exaggerated. The exaggerated condition was defined as a performance where musicians would exaggerate the acoustic parameters, whereas the deadpan condition would refer to a performance with limited expressive content. In the exaggerated condition, musicians' movements were larger than in the projected one. Moreover, [64] found that while the swaying motion that emanates from the hip region may not be easily visible when pianists perform in a deadpan performance, the motion was still present but at a much smaller scale. However, the relationship between the pianists' swaying action and the musical structure was still not clear [62]. A strong relationship was also observed between pianists' facial expression and body movements, which were linked to specific structural elements of the music [63]. In another study where pianists were asked to play an excerpt from the Beethoven Sonata No.4, Op.102/1, in different modes (i.e. personal, sad, allegro, overly expressive, serene), the quantity of motion was not influenced significantly by the performance modes, whereas the velocity of the head motion was [33]. [252] observed the movements of clarinetists while they were asked to perform Stravinsky's Three Pieces for Solo Clarinet in a standard, expressive and immobile manner. The immobile performance consisted of playing the piece with as little movement as possible. The results showed that clarinetists had not suppressed completely their movements, which suggests that certain movements are too ingrained in performers' technique and mental representation to be modified or removed totally. Bell motion in clarinet playing has also been associated to the reinforcement of idiomatic acoustic events at phrase boundaries and at places with harmonic tension [230]. Similarly, [232] used the same three conditions as in [252] and added the deadpan condition previously used in Davidson's research, to examine pianists' movements in relation to the musical structure of the Chopin's Prelude in E minor Op. 28, No. 4. The authors showed that the quantity of motion was modified in specific regions such as the ones with articulations, dynamic markings and at the piece's climax, and that the exaggerated condition was performed with larger quantity of motion in sections with these specific characteristics.

The following studies suggest that musicians' movements are often related to the rhythmic and phrasing structure of an excerpt, as well as to its technical difficulty and character. In order to identify the relationships between the rhythmic structure and similarity in upper body movements, pianists played two Chopin Preludes, similar in character, but different in terms of the phrasing structure [156, 157]. Pianists performed different phrases, with analogous rhythmical patterns, from Chopin's preludes using similar motion profiles. This suggests that different pianists shape their movements with respect to the phrasing structure and to the rhythm of the piece. However, while pianists' swaying movements were synchronized with the rhythmical patterns in simple piano pieces, it was suggested that this may not be the case for more complex excerpts [28]. Indeed, the periodic swaying motion observed in a pianist's head while performing a Scriabin Etude did not synchronize with the two-bar phrasing structure but was rather correlated with the emotional intensity. The difficulty and the structural characteristics of the different pieces may have had an impact on the synchronization of the movements with the rhythm, as well as on the recurrence of movements between performers.

Other studies investigated the impact of movements on auditors' judgment of musical performances and assessed which parts of the body better convey the expressive intention or emotion of the performance. In piano performance, head and upper torso movements provided meaningful information to auditors, who were asked to discriminate between performance conditions, while the hand movements did not [61]. [28] analyzed the expressive movements of a pianist performing a Scriabin Etude in normal and exaggerated conditions and identified that the most efficient auditory and visual cues for the pianist to communicate his expressive intentions were key-velocity, inter-onset-intervals (IOIs) and head movement velocity. Similarly, studies conducted on marimba players investigated the extent to which emotional intentions (i.e. happy, sad, angry, fearful) were conveyed through musicians' movements [53, 54]. By itself, the head movements appeared to provide sufficient information for observers to recognize the emotions conveyed by the performer. [175] analyzed observers' perception of clarinetists' performances of the Brahms Clarinet Sonata Op. 120, No. 1, when clarinetists' movements are modified. For instance, the motion of different body parts in a video recording was frozen while auditors were judging different parameters. It appeared that freezing the motion of the arms or torso in kinematic displays of clarinet performances do not affect observers' perception of fluency, tension and intensity of the performances [175]. Moreover, the authors showed that, although performers' movements present consistencies, the total amount of movement and the velocity differ for different body parts. For instance, when one player used larger arm motions, another one performed with more body sway. It was also shown that, during technically challenging passages, the movements seemed to be localized to certain body parts and their amplitude were reduced [175, 252]. It was suggested that this might possibly prevent fatigue and injury, or may facilitate precise execution.

Expressive manipulations and musical individuality of music performances have been linked mainly to temporal variations [92, 181]. [89] found that fast tempi were related to expressions of excitement and surprise, while slow tempi were associated with calmness, boredom and sadness. Moreover, a covariation of timing and dynamics tends to occur at the beginning [39] and the end of phrases [183, 201]. Because expression was associated with the magnitude of tempo variations, different expressive conditions were used to evaluate performers' rhythmical strategies to convey these expressions. In their 2005 study of clarinetists' movements, [252] found that the immobile condition was performed faster than the standard and exaggerated conditions, suggesting that motion is associated with the rhythmic structure of phrases. [232] revealed that pianists' tempo was also affected when performing a Chopin Prelude. They looked at each measure separately and found that the exaggerated performances were played slower on average, whereas the deadpan ones were the fastest compared to the standard performances. These tempo variations occurred during specific moments, such as phrase boundaries, or passages with harmonic tension. Contrary to Wanderley and colleagues' findings, the immobile and standard performances were quite similar in duration and pianists could still use tempo variations to perform in an immobile performance. The fact that the deadpan condition was not used in [252]'s study and that the respective complexity of the excerpts in both experiments was different may explain these different results.

Although previous research has focused on the expressive intentions a performer conveys to an audience, it is not clear yet how the structural parameters of musical excerpts with various technical difficulties are embodied in pianists' physical gestures. The study of different Romantic excerpts with various levels of complexity performed by a group of pianists may yield different results that may eventually clarify how auditors perceive and react to musical gestures and expression. This study seeks to understand better how experienced pianists use body movements and timing in relation to structural parameters of pieces with varied difficulties and contexts. First, we evaluate how pianists modulate their performances in terms of duration and quantity of motion (QoM) when asked to play excerpts from the Romantic period in different performance conditions. Second, we investigate how both the structural characteristics of the pieces and the conditions impact the pianists' body movements. Third, we analyze the recurrent patterns of head movement among all pianists when performing in a normal condition. The aim is to visualize where in the score do pianists tend to move in a similar way to understand whether certain movements are dependent on the musical parameters or the physical constraints brought by the instrument. Finally, we assess whether pianists are aware of the way they use body movements in relation to the musical structure and the various expressive conditions. The goal of this research is not to assess whether pianists express their ideas intentionally or not, but to observe the trends and differences among a group of pianists and how various musical excerpts influence body movements and expression. The survey provided us with additional information as regard pianists' expressive decisions and intentions. We hypothesize that the movements from the extremities of the body, such as the ones from the hand or head, will be more accentuated when exaggerating or limiting the expression and that they will vary according to the excerpt performed. We propose that changes in amplitude of movements will be restrained in more demanding passages, such as chromatic passages, and that tempo will be more affected in the deadpan and exaggerated conditions than in the immobile one.

4.2 Method

4.2.1 Participants and musical tasks

Participants

Ten pianists (average of 29.6 years old, SD=5.8, 6 Female 4 Male) participated in this study. The participants were all graduate or post-graduate students (3 doctoral, 3 master's and 4 bachelor's degrees). All participants signed a consent form approved by the University ethics committee.

Pilot study

In a pilot study, which sought to evaluate pianists' body movements when performing different excerpts in terms of their structural features and technical levels, eleven pianists performed different Romantic excerpts three times in the following order: normal, deadpan, exaggerated and immobile conditions. Similarly to [60], [251] and [232], the deadpan condition was described as playing with a reduced level of expression, whereas the exaggerated one, as playing with an exaggerated level of expression. An immobile performance consisted of playing with only the essential movements to produce a normal performance. The high number of excerpts provided data to evaluate multiple parameters of expression such as rhythm, harmony, phrasing, articulation, timing and sound dynamic. Pianists performed each expressive condition three times for a total of 12 performances per pianist. For each pianist, no significant difference in quantity of motion (QoM) was found between all the performances of the same expressive condition. This pilot study allowed us to select three excerpts that demonstrated diverse and contrasting: 1) difficulties, characters and structural characteristics, and 2) data results.

Choices of excerpts

The three thirty-second Romantic excerpts chosen for the current study are listed below:

1. Medtner Sonata Reminiscenza Op.38 (mes. 253-274)
2. Chopin 4th Ballade (mes. 152-160)
3. Chopin Impromptu (mes. 43-51)

Table 4.1 shows an analysis, conducted by the authors, of the structural characteristics for each excerpt and summarizes the results obtained for each pianist who performed the three excerpts as part of the pilot study.

For the rest of the article, each excerpt will be referred to as the 'Sonata', the 'Ballade' and the 'Impromptu'. Each excerpt was performed in the same four expressive conditions as used in the pilot study (normal, deadpan, exaggerated and immobile conditions). The pianists played each excerpt once in each expressive condition (for total of 12 performances per pianist). Participants could choose the tempo they found appropriate to convey the expressive conditions. The order of excerpts was randomized for each participant.

Table 4.1 Analysis performed by the authors of each excerpt's structural characteristics and summary of results from previous measurements.

Structural characteristics		
Medtner Sonata Reminiscenza	**Chopin 4th Ballade**	**Chopin Impromptu**
-Very dynamic and changing character -Many ascending movements and long arpeggios -Crescendo dynamic -Many accentuated chords and notes -Varied rhythm -Dominant chords -Chromatic passages -Repetitions and modulations	-Impetuous and constant character -Polyrhythm between the hands (constant ternary rhythm at the left hand vs rhythmically unstable melody at the right hand) -Few moments of rest -Chromatic melody with few 8ve intervals that create tension -Repetitions and modulations	-Peaceful and gentle character -Simple melody -Slow and regular rhythm -Smooth dynamics and articulations -Ornaments -Repetitions and modulations
Results from the pilot study		
Medtner Sonata Reminiscenza	**Chopin 4th Ballade**	**Chopin Impromptu**
-All conditions performed faster than normal -Large variations in QoM in the deadpan and immobile performances as compared to the normal condition -Hand movements in the z-axis vary more than other body parts between expressive conditions -Variations in amplitude of hand movement related to the loud dynamic level and accentuated chords -Similar QoM in the normal and exaggerated performances	-All conditions performed slower than normal -Smallest variations in QoM between the normal, deadpan and immobile conditions -Large variations in QoM between the normal and exaggerated conditions -Large amplitude of head motion observed in the exaggerated condition during the return of the main theme and 8ve interval in the melody -Head movement is periodic and follows the rhythm at the left hand, even in the immobile condition	-Exaggerated and immobile performance performed faster than normal and deadpan condittions -Largest differences in QoM between the conditions -Large amplitude of the head motion in the normal performance in the middle of phrases, and at the beginning of phrases for the exaggerated performance -Deadpan and immobile conditions are performed with almost no variations in amplitude of head movement

4.2.2 Measurements

At the beginning of the experiment, pianists filled in a demographic questionnaire and, at the end of the measurement session, pianists completed a survey to assess how they experienced body movements. Participants were asked questions on their understanding of the structure of the excerpts and how it influenced their musical interpretation. Performances were video recorded with a Sony Wide Angle video camera and audio recorded with a Sennheiser MKH microphone. Motion data were collected, at a rate of 240 frames per second, with a 17-camera Qualisys motion capture system, using 49 passive reflective markers put on the pianists' hands, elbows, shoulders, torso, head, and pelvis. The placement of markers on pianists' upper body and head is shown in Figure 4.1A. In order to perform the analysis and to extract different kinematic parameters, a set of 16 markers was derived from the marker locations (Figure 4.1B). The midpoint of a joint was obtained by averaging the location of two or more markers using the MATLAB Motion Capture (MoCap) Toolbox [20]. The beginning of each frame was time-stamped (SMPTE timecode) at 25 Hz, and a Rosendahl Nanosyncs HD word clock, sampled at 48 kHz, generated the clock signals for all the digital devices. The Rosendahl Nanosyncs was connected to the video camera, the Qualisys Sync Unit and the Fireface audio interface. The Qualisys Sync Unit converted the SMPTE signals so that it may be recorded by the mocap cameras. The audio recording was slaved to the video signal. The control computer recorded the audio and MIDI data from the MIDI keyboard with Reaper software and was connected to the same network as the Qualisys computer, which triggered the recordings of both Qualisys Track Manager (QTM) and the audio and MIDI from the keyboard using the OSC protocol.

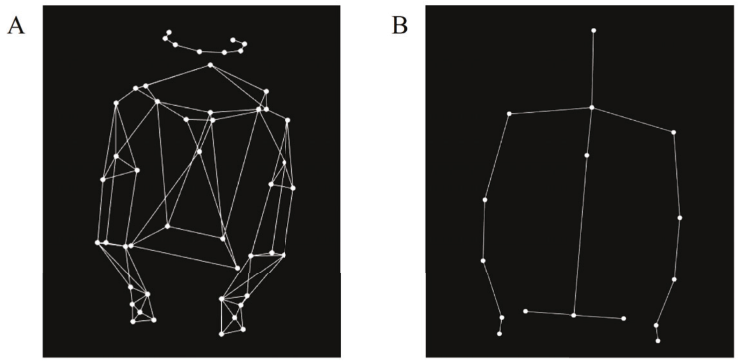

Fig. 4.1 **A** Anterior view of the location of markers attached to the pianists' upper body. **B** Anterior view of the joint representation of the pianists' upper body.

4.3 Data analysis

As discussed earlier, previous studies have shown that acoustical and kinematic parameters are important indicators of expression in piano performance. The term *kinematics* is used to describe the spatial details of the movement itself. Kinematics is not concerned with the internal or external forces that cause the movement [265]. The present kinematic analysis focuses on the total QoM and the position data in relation to each excerpt's structural parameters. The durations of the performances are also examined with regard to the performance conditions.

4.3.1 Note extraction and audio analysis

To measure the duration of each excerpt in each condition for every pianist, a filter was applied to the absolute value of the audio signal, using the Matlab function movmean, which calculates the moving average across a sliding window. The length of the window used was 200 frames for every participant. Then a sound intensity threshold of .001 dB was applied to the signal to mark the beginning and end of each performance. Since pianists could choose the tempo in which to perform each excerpt, the signals also needed to be temporally aligned to the musical structure. Therefore, the exact time of each important gestural event (i.e. notes or beats) was identified and annotated with the audio editor Audacity. The time coordinates of the position data were aligned to their corresponding musical events using a time-warping algorithm [243]. All pianists' position data were averaged, time warped and aligned to the score.

4.3.2 Movement analysis

First, we used principal component analysis (PCA) to determine which body parts vary the most across the performance conditions for each individual pianist. We calculated the cumulative QoM for all the body parts (i.e. head, torso, shoulders, elbows, hands and pelvis) using the MATLAB Motion Capture (Mocap) Toolbox [20]. The QoM of each body part was measured from the joint location data, for each performance condition, in the three axes of the coordinate system. The x-axis represents the motion along the keyboard, the y-axis accounts for the movement toward and away from the keyboard, and the z-axis represents the movement of the body going up and down. This yielded a total of 27 variables for each of the ten pianists playing in the four expressive conditions. We applied PCA on the matrix of kinematic values to reduce the number of relevant features (i.e. body parts and directions of the movements) required to identify which body parts fluctuate the most across conditions for each individual pianist. We identified the first PC and its corresponding feature with the highest coefficient for each pianist. The coefficient is a measure of how each variable contributes to the principal components.

After identifying these body parts, we measured the absolute difference in the total QoM between each condition and the normal condition. We calculated the cumulative distance traveled by the markers to analyze the differences between the expressive conditions. All pianists' cumulative QoM values were averaged together. For each excerpt, the QoM of the normal performances was taken as a reference point (0%) to compare against the values obtained in the other conditions. Then, a series of one-way ANOVAs was conducted for each measure to identify whether there were significant differences between the conditions.

4.3.3 Movement recurrence

In order to identify the sections of the score in which pianists perform with similar movements and to find the common patterns within the time-series of the position data, we used the instantaneous correlation algorithm developed by [244]. The algorithm measures the correlation coefficient between pairs of signals for each frame and generates a bi-dimensional correlation map that reveals the regions of high recurrence between all pairs of signal (i.e. recurrence of movement patterns). The same threshold used in [230] was applied to the map, removing all values below 0.75. We examined the Euclidean norm of the position data together with the correlation map to facilitate the display of the pianists' movement patterns.

4.4 Results

This section reports the results on a) the overall duration of the performance, b) the quantity of motion, and c) the recurrence of movements.

4.4.1 Overall duration of the performances

To evaluate how pianists vary the tempi in relation to the levels of expression and the different excerpts, we calculated the duration of every performance (total of 12 per pianist). The lengths of the performances are indicated in Table 4.2 per pianist and per excerpt.

Table 4.2 Timing of performances of each condition for all pianists.

		Medtner Sonata Reminiscenza		**Chopin 4th Ballade**		**Chopin Impromptu**	
	Performance conditions	Time (s)	% difference compared to normal	Time (s)	% difference compared to normal	Time (s)	% difference compared to normal
P1	Normal	43.32		25.89		31.97	
	Deadpan	39.21	-9.98	25.08	-3.20	28.57	**-11.23**
	Exaggerated	48.50	**+11.27**	28.98	**+11.24**	34.87	+8.68
	Immobile	41.29	-4.80	23.59	-9.30	30.85	-3.57
P2	Normal	47.88		29.25		31.21	
	Deadpan	55.83	**+15.31**	33.49	**+13.52**	39.64	**+23.77**
	Exaggerated	44.71	-6.86	29.57	+1.09	32.75	+4.81
	Immobile	50.2	+4.73	30.79	+5.13	28.28	-9.88
P3	Normal	40.45		26.98		32.29	
	Deadpan	45.74	**+12.27**	27.10	+0.45	30.77	-4.82
	Exaggerated	40.53	+0.19	23.95	**-11.88**	30.01	**-7.33**
	Immobile	42.44	+4.81	25.86	-4.22	31.33	-3.04
P4	Normal	39.12		24.12		32.60	
	Deadpan	36.48	**-6.99**	21.28	**-12.51**	27.74	**-16.10**
	Exaggerated	41.44	+5.76	26.40	+9.03	34.73	+6.31
	Immobile	39.01	-0.28	24.25	+0.54	33.35	+2.28
P5	Normal	35.59		25.70		39.93	
	Deadpan	38.56	+8.00	25.55	-0.60	38.26	-4.27
	Exaggerated	42.59	**+17.90**	27.05	**+5.12**	42.44	**+6.11**
	Immobile	36.93	+3.69	26.56	+3.28	38.32	-4.12
P6	Normal	37.40		25.85		35.16	
	Deadpan	34.85	**-7.07**	24.27	**-6.32**	31.95	**-9.57**
	Exaggerated	39.55	+5.57	26.38	+2.02	35.46	+0.84
	Immobile	39.25	+4.82	25.80	-0.19	35.95	+2.21
P7	Normal	43.11		39.91		39.27	
	Deadpan	41.06	**-4.87**	41.51	+3.91	38.95	-0.82
	Exaggerated	42.79	-0.75	45.86	**+13.86**	40.53	**+3.15**
	Immobile	43.67	+1.30	42.01	+5.13	39.92	+1.63
P8	Normal	41.20		35.74		36.39	
	Deadpan	43.11	+4.53	37.05	+3.58	36.15	-0.67
	Exaggerated	45.08	+8.98	35.78	+0.10	35.87	**-1.43**
	Immobile	45.34	**+9.55**	39.79	**+10.72**	36.25	-0.38
P9	Normal	47.36		34.74		39.71	
	Deadpan	46.37	**-2.11**	34.36	-1.08	33.76	**-16.21**
	Exaggerated	47.38	+0.04	33.15	**-4.67**	38.20	-3.86
	Immobile	46.65	-1.51	33.90	-2.45	37.49	-5.75
P10	Normal	42.64		41.31		35.47	
	Deadpan	46.07	+7.73	44.12	+6.59	34.56	-2.61
	Exaggerated	48.03	**+11.9**	47.02	**+12.94**	38.47	**+8.12**
	Immobile	43.63	+2.30	43.28	+4.67	33.70	-5.12

We did not observe any clear pattern between the pianists and conditions in terms of tempi and excerpt lengths: each pianist employed different tempi to perform the excerpts and conditions. Overall, 63% of the deadpan performances and 47% of the immobile performances were performed faster than the normal ones. The exaggerated performances were mostly performed at a slower tempo than the normal ones for all the excerpts (i.e. 8 pianists in the Sonata and in the Ballade, and 7 pianists in the Impromptu). Pianist 2 was the only one to perform all the excerpts slower in the deadpan performance with a percentage difference of 15.33% for the Sonata, 13.52% for the Ballade and 23.77% for the Impromptu, which also corresponds to the largest difference in duration among all pianists.

Figure 4.2 shows the mean duration of performances and the associated standard deviations between participants and Figure 4.3 indicates the differences in duration for each measure per condition. The duration of the normal performances, represented by the red line, was taken as a reference (0%) to compare against the values obtained in the other conditions.

Tempo and musical excerpts

Medtner Sonata Reminiscenza. As demonstrated in Figure 4.2, the largest average duration for the Sonata occurs in the exaggerated performances (M=44.06, SD=3.19), with a mean percentage difference of 5.24 as compared to the normal performance and the discrepancy among pianists is greater in the deadpan condition (M=42.71, SD=6.14). The smallest deviations in duration from the normal performance occur in the immobile condition with a mean difference of 2.46% slower than the normal condition. The majority of the pianists played the exaggerated (n=8) and immobile (n=7) conditions slower than the normal condition, whereas only half (n=5) of them played the deadpan condition faster. For seven pianists, the smallest variations in duration are observed between the immobile and normal conditions. Although no significant differences were found between the conditions, Figure 4.3 indicates that the deadpan and exaggerated performances vary more from the normal condition than the immobile performance, but not necessarily at the same places. For instance, while pianists perform the exaggerated condition faster during bars 13 and 14 (fast arpeggio in a crescendo dynamic), these measures are played almost with the same duration in the deadpan condition as in the normal one, whereas the opposite occurs during bars 15 to 18 (series of accentuated chords).

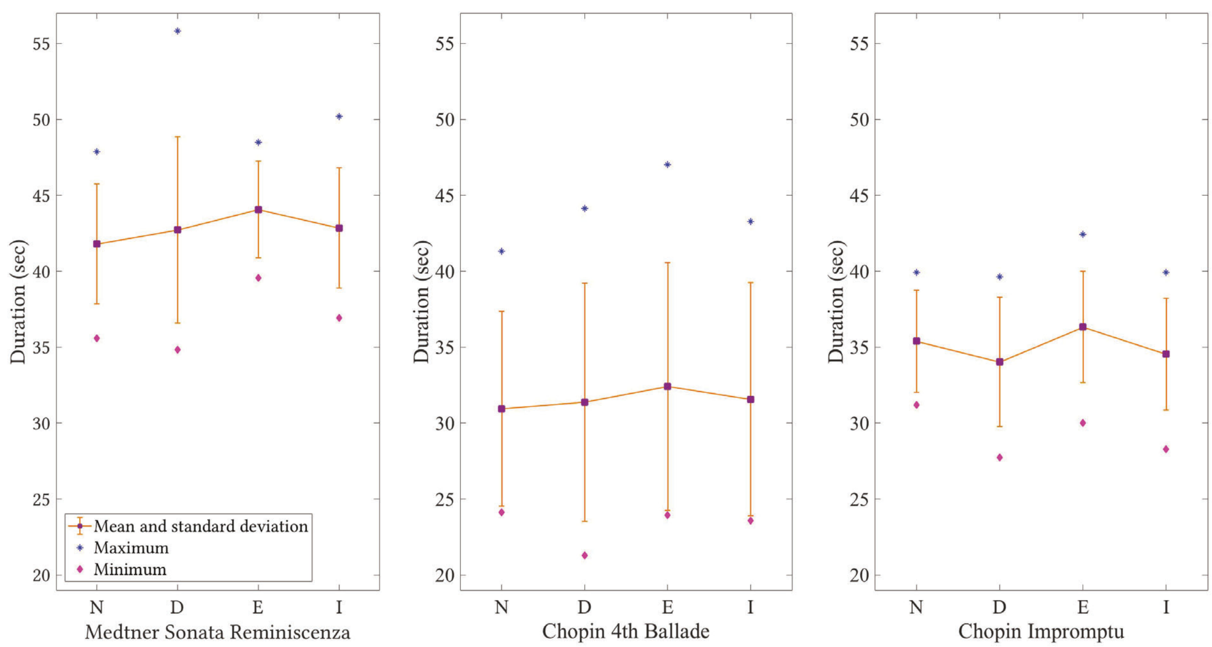

Fig. 4.2 Mean duration of performances for each condition and excerpt. The purple squares show the mean duration and the yellow bars the standard deviation between participants. The blue stars represent the longest performances, while the pink diamonds show the shortest ones. (N=Normal, D=Deadpan, E=Exaggerated, I=Immobile).

Chopin 4th Ballade. As shown in Figure 4.2, the durations differ greatly among pianists for all the conditions as exemplified by the high standard deviations, and especially in the exaggerated condition (M=32.41, SD=8.16). The mean duration of the Ballade performed in the four conditions demonstrates smaller differences than for the other excerpts, with a maximum percentage difference of 4.62 in the exaggerated condition (Figure 4.3). Similarly to the Sonata, most of the pianists performed the immobile (n=6) and exaggerated (n=8) conditions at a slower tempo, whereas five only played the deadpan condition faster. As Figure 4.3 demonstrates, almost no changes in the measure lengths are perceptible between the expressive conditions.

Chopin Impromptu. Contrary to the other two excerpts, pianists tend to perform the immobile condition faster (n=7) in the Impromptu. Most pianists (n=9) performed the deadpan condition faster than the normal condition, with a percentage difference of 4.25. The duration of performances varies almost equally between pianists and conditions, but slightly more in the deadpan performance (M=34.04, SD=4.25). Statistical variations were found for bar 7 only in the Impromptu [$F(3, 36) = 3.3$, $p < .05$] as indicated with a Tukey's Honest Significant Test (HSD) (Figure 4.3). The discrepancy in duration which occurs between the deadpan and exaggerated performances may be explained by the ornaments and rubato during that passage.

4.4.2 Head quantity of motion

PCA was used in order to verify which body parts were the most altered when pianists perform in various expressive conditions. Table 4.3 indicates the first PC and its corresponding component feature with the highest coefficient for all pianists and each excerpt, as well as their respective level of variance across the expressive conditions. The percent variability explained by the first PC provides a sufficiently complex profile to differentiate between the expressive conditions, with a minimum percentage of variance of 85.18 for pianist 10. For the three excerpts, the main component feature that varies the most in terms of QoM across the conditions is the head, and more specifically in the y-axis, that is towards and away

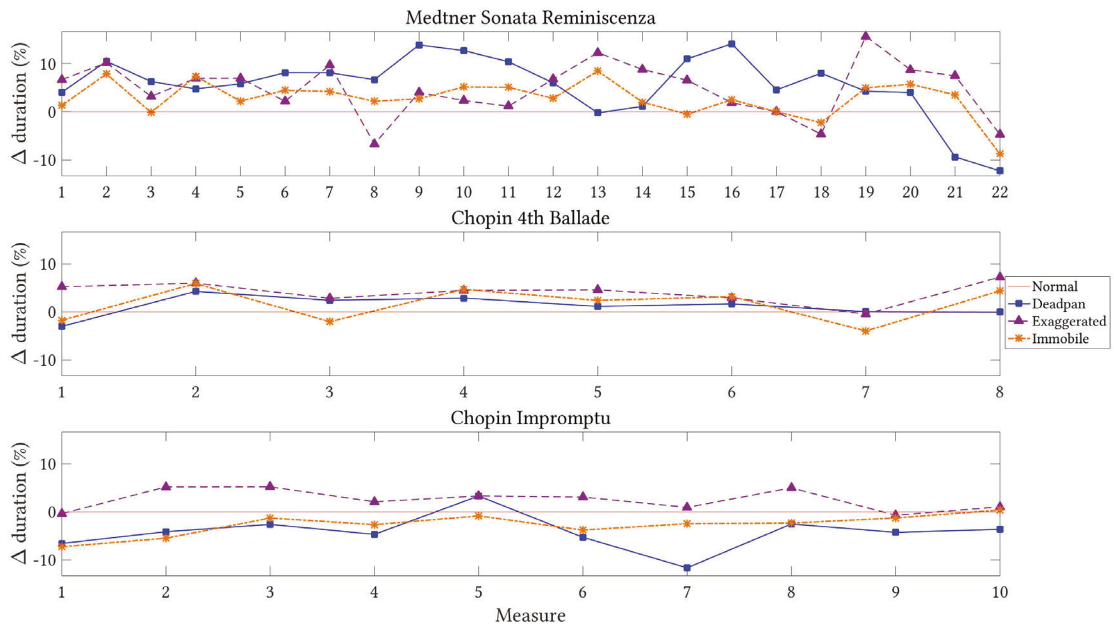

Fig. 4.3 Absolute difference in percentage of duration for each measure per condition. The red line represents the reference point, the normal condition, against which the other conditions are compared.

from the piano. However, for pianist 2, the right hand is the body part that shows more variations in movement amplitude, in the z-axis (up and down) during the performances of the Sonata, while pianist 10 moves the left elbow with more variations in the x-axis (along the keyboard) during the Impromptu. Moreover, the amplitude of the head in the x-axis differs more for three pianists in the Sonata, for five in the Ballade and for four in the Impromptu. As the PCA revealed that, in general, pianists modulate the amplitude of the head movement when performing various expressive conditions, we decided to analyze more carefully these head movements as relate to the structural characteristics of each excerpt.

Table 4.3 First PC's component feature and level of variance (in %) across all expressive conditions and excerpts for all pianists.

	Medtner Sonata Reminiscenza		Chopin 4th Ballade		Chopin Impromptu	
Pianists	PC1 component	Variance (%)	PC1 component	Variance (%)	PC1 component	Variance (%)
P1	head x-axis	95.89	head x-axis	95.69	head x-axis	94.82
P2	rhand z-axis	94.62	head y-axis	84.45	head y-axis	89.41
P3	head y-axis	95.95	head y-axis	96.12	head x-axis	94.56
P4	head y-axis	96.79	head x-axis	93.63	head y-axis	91.66
P5	head y-axis	95.94	head y-axis	94.78	head y-axis	98.01
P6	head y-axis	98.88	head y-axis	98.44	head y-axis	98.48
P7	head x-axis	91.18	head x-axis	96.66	head y-axis	98.66
P8	head y-axis	89.88	head x-axis	93.03	head x-axis	96.95
P9	head y-axis	97.53	head y-axis	98.17	head y-axis	99.00
P10	head x-axis	85.18	head x-axis	94.72	lelbow x-axis	96.50

Head QoM and musical excerpts

Figure 4.4 illustrates the mean QoM and standard deviation for each condition and excerpt. Figure 4.5 shows the absolute difference of QoM for each measure between the expressive conditions and the normal one. To identify the regions in the score where the amplitude of the head movement differs significantly between the normal and the other expressive conditions, we conducted a series of one-way ANOVAs on the head position data for each excerpt and each measure. A Tukey's Honest Significant Test (HSD) showed which of the expressive conditions differed significantly. The results of the one-way ANOVAs are shown in Tables 4.4, 4.5 and 4.6 and the corresponding regions where statistical differences between the conditions occur are displayed in Figure 4.6. For all excerpts, there was no significant difference between the normal and exaggerated conditions, and between the deadpan and immobile conditions.

Medtner Sonata Reminiscenza. During performances of the Sonata, pianists used on average 20.61% more QoM in the exaggerated condition than in the normal one, significantly higher than for the other two excerpts. Figure 4.4 shows that the largest discrepancies in

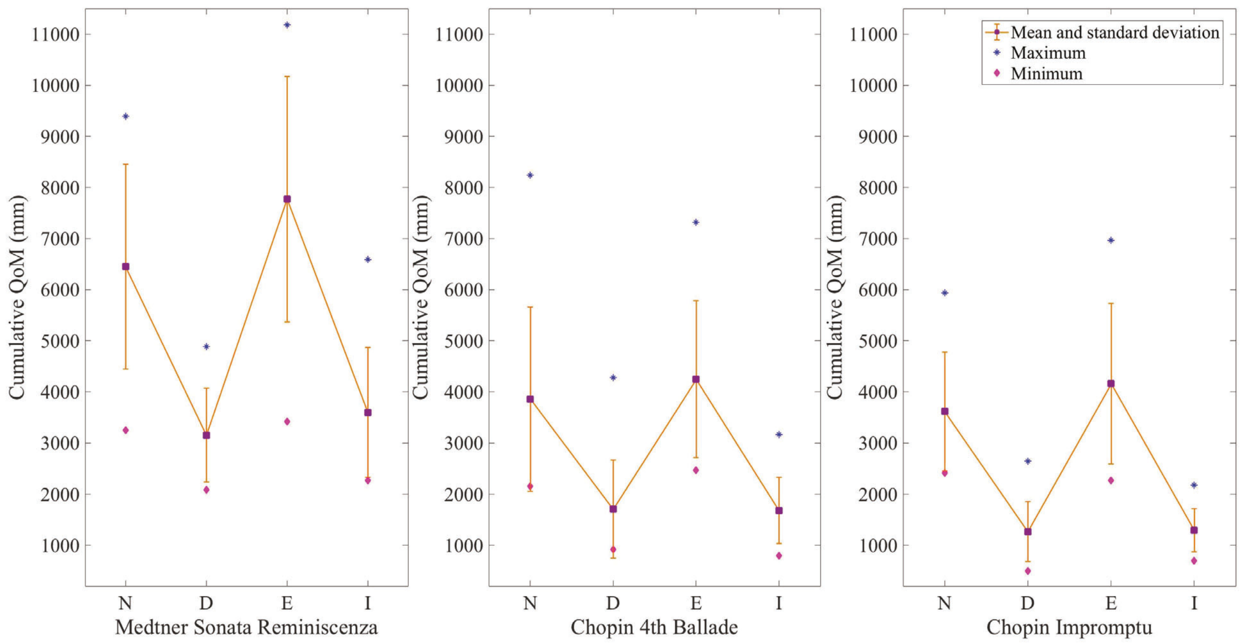

Fig. 4.4 Mean cumulative head QoM for each condition and excerpt. The purple squares show the mean QoM and the yellow bars the standard deviation between participants. The blue stars represent the largest values, while the pink diamonds show the smallest ones. (N=Normal, D=Deadpan, E=Exaggerated, I=Immobile).

head QoM between pianists occur in the exaggerated condition (M=7774.23, SD=2402.15). Differences in mean cumulative QoM between the deadpan and normal, and immobile and normal conditions are larger than between the exaggerated and normal conditions, more specifically between bars 4 and 6 for the deadpan condition, and between bars 16 and 17 (Figure 4.5). As shown in Table 4.4, the normal performance varies significantly with the deadpan and immobile conditions in region A (bars 1 to 4), region B (bar 13) and region D (bars 19 to 21), and with the deadpan condition only in region A (bars 5 to 7) and region C (bars 16 and 17). Sections A, B and D contain ascending chromatic movements in a crescendo dynamic, and the climax of the excerpt is found in section B (Figure 4.6). Section D starts with a series of fast and accentuated chords, followed by a German sixth

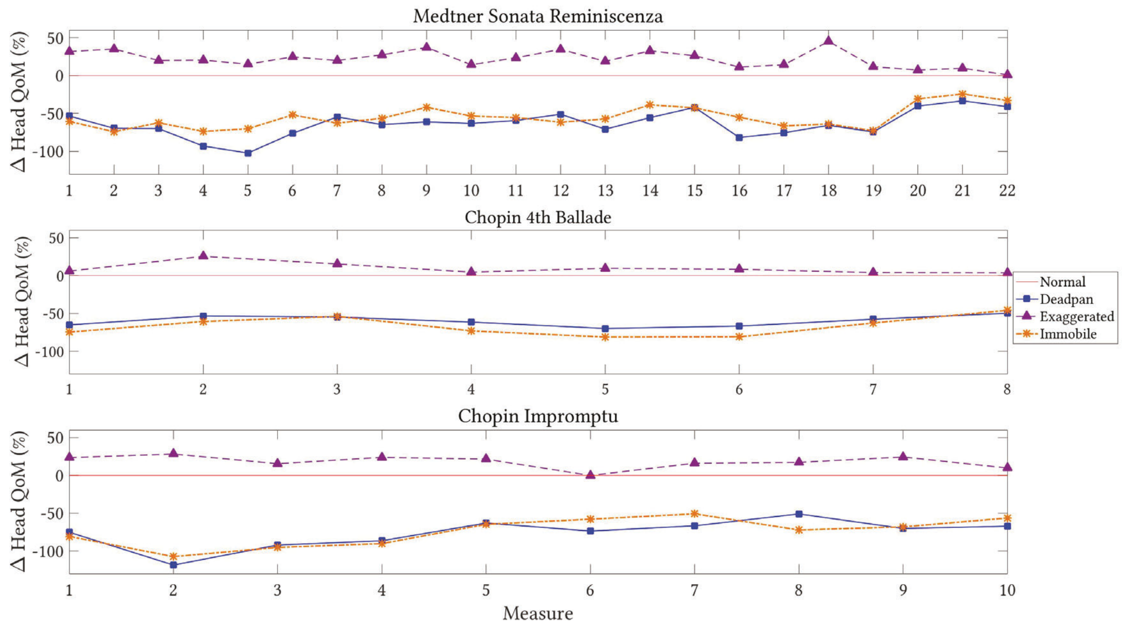

Fig. 4.5 Absolute difference in percentage of head QoM for each measure per condition. The red line represents the reference point, the normal condition, against which the other conditions are compared.

chord and a long ascending motion that finishes on a high pitch note at the beginning of measure 21. For all these regions, the head QoM is more reduced in the deadpan performance than in the immobile condition as compared to the normal performance. Pianists did not modulate significantly their movements in the exaggerated condition as compared to the normal condition.

Chopin 4th Ballade. As revealed in Figure 4.4, the smallest variations, across all excerpts, between the exaggerated and normal conditions occur in the Ballade (M=4247.36, SD=1535.17). Moreover, pianists reduce the movement and move the head similarly in the immobile and deadpan conditions (Figure 4.5). Both conditions mark a clear distinction with the normal and exaggerated conditions. Table 4.5 shows that significant differences in the amplitude of the head movement between the deadpan and immobile conditions and the normal one occur in three regions. In these three regions, the normal performance differs significantly from both the deadpan and immobile performances, except in bar 3 where it differs significantly with the deadpan condition only. As shown in Figure 4.6, section A is characterized by the exposition of the theme, section B by a short moment of rest at the right hand before the return of the melody, and section C by a large interval (8ve) in the melody adding tension. The exaggerated condition does not differ significantly from the normal performance.

Chopin Impromptu. As shown in Figure 4.4, deviations in the head QoM between pianists' performances of the Impromptu are smaller in the normal, deadpan and immobile conditions than for other excerpts (normal: M=3616.89, SD=1163.57; deadpan: M=1265.65, SD=585.02; immobile: M=1291.60, SD=422.96). As shown in Figure 4.5, the deadpan and immobile conditions require less movement than the normal one, with respectively 89.55% and 88.22% of the movement used during the normal performance. The head QoM in the normal performance differs significantly from both the deadpan and immobile performances for the whole excerpt (Table 4.6). The excerpt is characterized by a slow modulating melody (region B) and a reiteration of the main theme in the original key (region C) (Figure 4.6). Surprisingly, for that excerpt, pianists did not modify the head motion significantly between the exaggerated and normal performances.

Table 4.4 Medtner Sonata Reminiscenza - Results from the one-way ANOVA performed on the cumulative distance traveled by the head marker for the regions presenting significant differences between the normal condition and the other expressive conditions. The last two rows indicate pair-wise comparisons (Tukey-Kramer) significant at $p < .05$.

			Tukey's HSD Comparisons	
		$F(3, 36)$	p	Conditions
Region A	Bar 1	11.6	.009	Normal-Deadpan
			.01	Normal-Immobile
	Bar 2	11.9	.05	Normal-Deadpan
			.04	Normal-Immobile
	Bar 3	10.5	.007	Normal-Deadpan
			.03	Normal-Immobile
	Bar 4	12.3	.003	Normal-Deadpan
			.01	Normal-Immobile
	Bar 5	11.1	.01	Normal-Deadpan
	Bar 6	8.9	.01	Normal-Deadpan
	Bar 7	12.8	.05	Normal-Deadpan
Region B	Bar 13	11.9	.004	Normal-Deadpan
			.01	Normal-Immobile
Region C	Bar 16	6.2	.03	Normal-Deadpan
	Bar 17	9.2	.005	Normal-Deadpan
Region D	Bar 19	9.4	.02	Normal-Deadpan
			.02	Normal-Immobile
	Bar 20	14.7	$< .001$	Normal-Deadpan
			.001	Normal-Immobile
	Bar 21	13.2	.002	Normal-Deadpan
			.007	Normal-Immobile

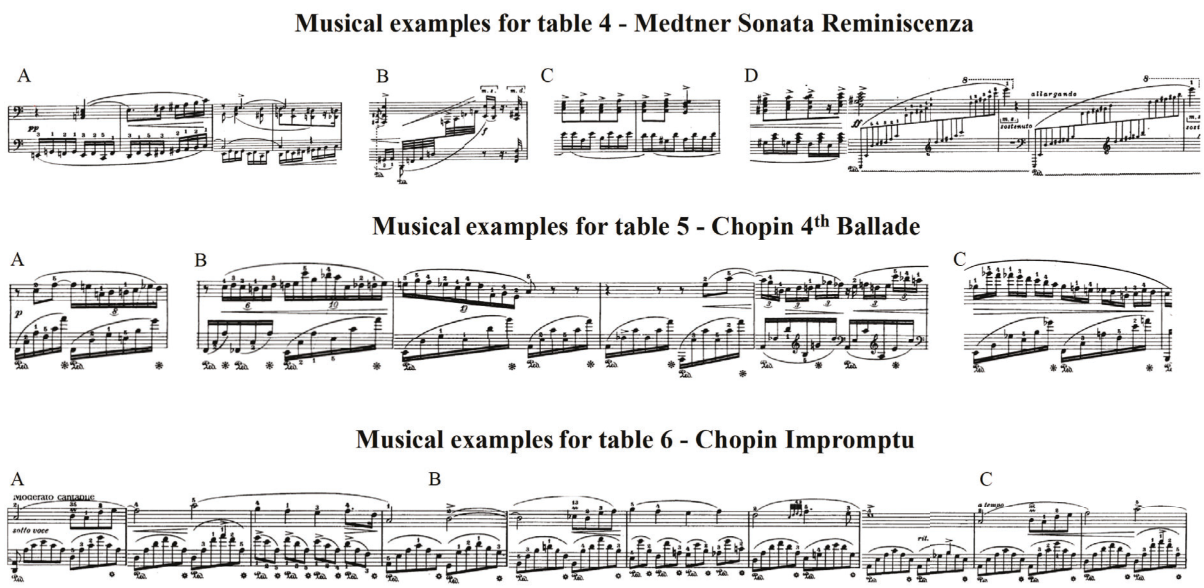

Fig. 4.6 Musical examples for tables 4 to 6 corresponding to each excerpt and each region that are significantly different between the expressive conditions.

Table 4.5 Chopin 4th Ballade - Results from the one-way ANOVA performed on the cumulative distance traveled by the head marker for the regions presenting significant differences between the normal condition and the other expressive conditions. The last two rows indicate pair-wise comparisons (Tukey-Kramer) significant at $p < .05$.

			Tukey's HSD Comparisons	
		$F(3, 36)$	p	Conditions
Region A	Bar 1	7.1	.02	Normal-Deadpan
			.01	Normal-Immobile
Region B	Bar 3	6.2	.04	Normal-Deadpan
	Bar 4	16.3	.001	Normal-Deadpan
			$< .001$	Normal-Immobile
	Bar 5	9.8	.008	Normal-Deadpan
			.01	Normal-Immobile
	Bar 6	6.2	.05	Normal-Deadpan
			.03	Normal-Immobile
Region C	Bar 8	26.9	$< .001$	Normal-Deadpan
			$< .001$	Normal-Immobile

Table 4.6 Chopin Impromptu - Results from the one-way ANOVA performed on the cumulative distance traveled by the head marker for the regions presenting significant differences between the normal condition and the other expressive conditions. The last two rows indicate pair-wise comparisons (Tukey-Kramer) significant at $p < .05$.

			Tukey's HSD Comparisons	
		$F(3, 36)$	p	Conditions
Region A	Bar 1	17.1	.002	Normal-Deadpan
			.003	Normal-Immobile
	Bar 2	22.6	$< .001$	Normal-Deadpan
			$< .001$	Normal-Immobile
	Bar 3	18.8	$< .001$	Normal-Deadpan
			$< .001$	Normal-Immobile
Region B	Bar 4	14.6	.004	Normal-Deadpan
			.005	Normal-Immobile
	Bar 5	9.1	.04	Normal-Deadpan
			.02	Normal-Immobile
	Bar 6	12.1	.001	Normal-Deadpan
			.001	Normal-Immobile
	Bar 7	8.9	.004	Normal-Deadpan
			.002	Normal-Immobile
	Bar 8	10.5	.01	Normal-Deadpan
			.002	Normal-Immobile
Region C	Bar 9	17.0	$< .001$	Normal-Deadpan
			.001	Normal-Immobile
	Bar 10	11.8	$< .001$	Normal-Deadpan
			.003	Normal-Immobile

4.4.3 Head movement recurrence

To assess whether several pianists embody the musical structure in a similar way, the head position data and the motion recurrence map analysis were used jointly. In the top graphs of figures 7 to 9, the Euclidean norm of the head position averaged and time-warped are shown in the four different conditions while all the pianists were playing the Sonata, the Ballade and the Impromptu. The bottom graphs show the correlation map which indicates the regions where the pianists used similar head movements. For instance, a large offset in certain regions means that the movement may have been initiated sooner or later depending on the pianist, but that all of the pianists performed with similar movements.

Medtner Sonata Reminiscenza. Figure 4.7 top graph shows that the changes in head amplitude for the Sonata coincides with rhythmical sections in the excerpts, at bars 13 and 20, which also display high recurrence in the head movement. Bar 13 starts with a large accentuated chord followed by an arpeggio and the last three bars (20-22) are characterized by two arpeggios that span five octaves. Four large offsets of one second are seen at the end of the excerpt, suggesting that pianists initiated the movement with either a delay or a lead of 0.5 sec.

Chopin 4th Ballade. The beginning of the Ballade is marked with several regions of recurrent movement patterns, as shown in Figure 4.8, which coincide with short rests in the melody. Pianists' head movement follows the rhythmic structure at the left hand, a ternary rhythm composed of sixteenth notes grouped in two segments for each measure in the four conditions with amplitude changing on every beat. This effect is more pronounced in the normal and exaggerated conditions than in the deadpan and immobile performances, mainly at the beginning of the excerpt and in the middle of bar 5. Another area where similar head movements are found is in the middle of bar 6, which corresponds to a sixteenth rest.

Chopin Impromptu. As Figure 4.9 shows, the Impromptu yields large variations in amplitude of the head motion between the conditions, and the deadpan and immobile conditions are performed with a reduced QoM. Only two short regions are performed with recurrent patterns of movements, which is not surprising given the great variations between the conditions. The first region at bar 1 coincides with the beginning of the main theme, which is repeated towards the end at bar 9. The second region is performed similarly among pianists and marks the end of the excerpt on the dominant chord.

4.4.4 Survey

Pianists filled in a survey about their perception of how they move in relation to the musical score. The survey includes open-ended questions related to the strategies pianists employed to convey the different expressive conditions, as well as to the types of movements they used to communicate the musical structure. Pianists' answers to the survey were then used to compare the movement data with pianists' personal assessment of their movements.

- *Question 1.* While performing, do you solicit a specific part of the body? If so, why?

Most of the pianists mentioned that the arms are important for a better control of the fingers and the keys, and to play in a more natural and fluid manner. Using arm weight helps staying connected with the rest of the body and the instrument. The torso and head are generally used to communicate creativity and emotional investment. The hips, although less often mentioned than arms, help project the sound and are used for openness.

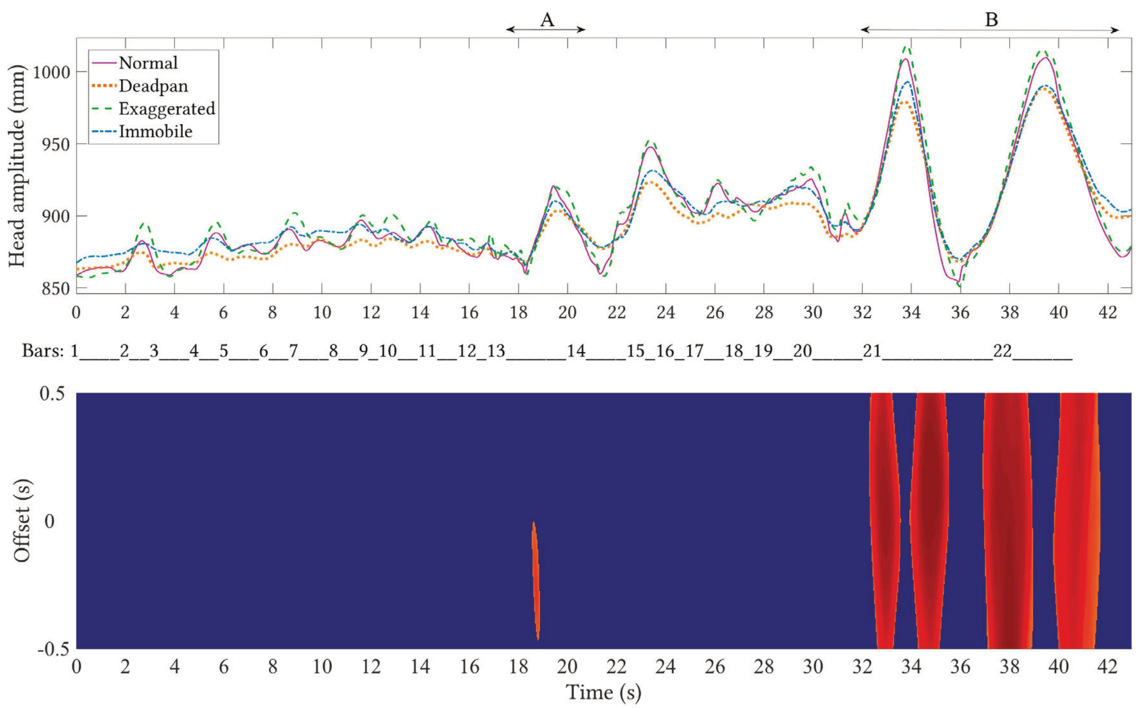

Fig. 4.7 Medtner Sonata Reminiscenza - Top plot: average time-warped amplitude of the head movement in the four expressive conditions. The arrows delimitate the regions of interest. Bottom plot: motion recurrence map indicating the regions with high recurrence (red regions).

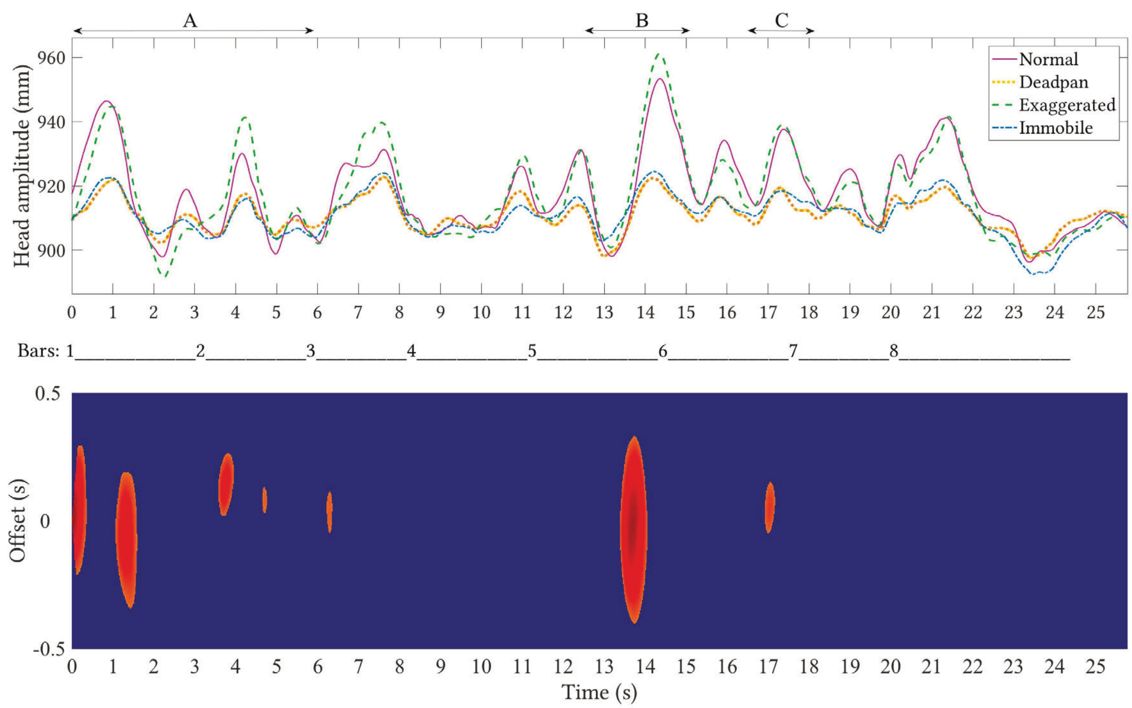

Fig. 4.8 Chopin 4th Ballade - Top plot: average time-warped amplitude of the head movement in the four expressive conditions. The arrows delimitate the regions of interest. Bottom plot: motion recurrence map indicating the regions with high recurrence (red regions).

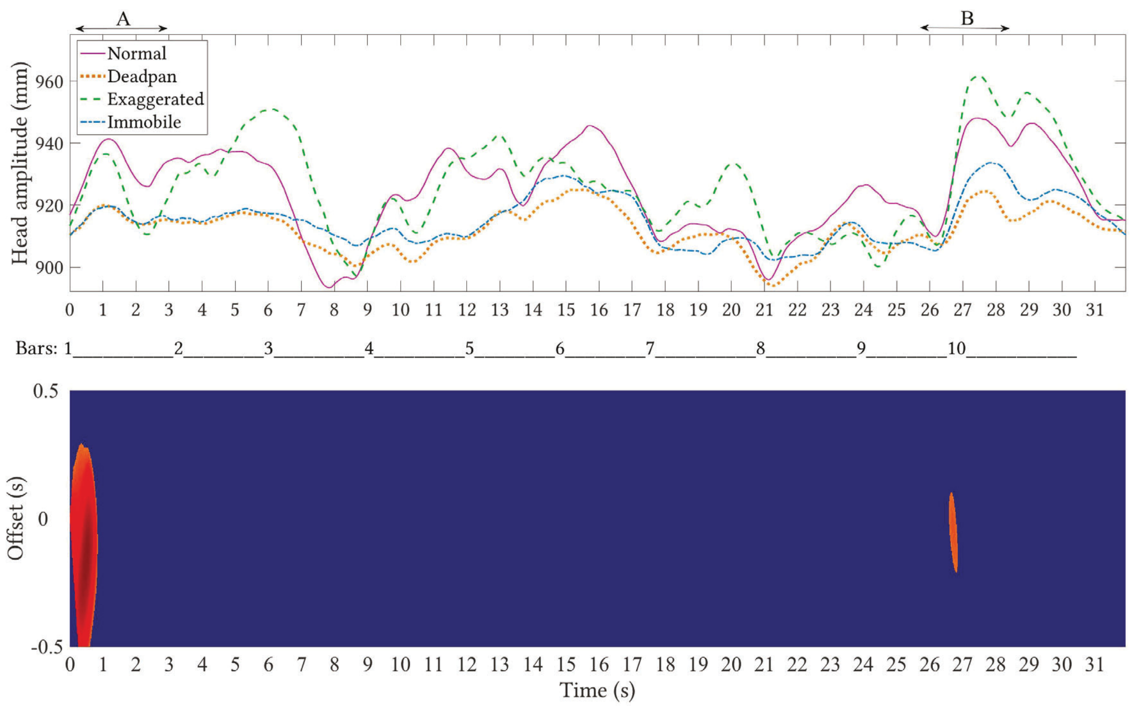

Fig. 4.9 Chopin Impromptu - Top plot: average time-warped amplitude of the head movement in the four expressive conditions. The arrows delimitate the regions of interest. Bottom plot: motion recurrence map indicating the regions with high recurrence (red regions).

- *Question 2.* Are you aware of any specific movements you used to communicate the different expressions?

Most of the pianists stated that during the deadpan performance they decreased the QoM by restricting mainly the motion from the head and arms. The exaggerated condition required them to move with more amplitude, more arm motion and weight, and more hip movement. One pianist perceived that playing in the exaggerated condition created useless tension and imprecision in movements for all the excerpts, but particularly during the Ballade. For the same excerpt, two pianists reported that the immobile condition was easier to perform than the exaggerated condition because for that excerpt, playing with less movement is closer to a natural performance than playing with exaggerated ones. However, for the two other excerpts, pianists found that the immobile manner felt generally unnatural and prevented them from playing fluidly. To perform the immobile condition, they tried to limit the head and torso movements. However, playing with a restricted amount of movements while trying to be natural in the expression helped one pianist identify the regions in the score where excessive efforts were normally made. That pianist mentioned that, while restricting the movements, the focus was put on listening to the performance.

- *Question 3.* For each excerpt, do you think you moved according to the structure of the piece you performed? If so, how?

Pianists said that they used specific movement strategies to convey the respective structural parameters of each excerpt. Overall, pianists mentioned that the movements are mainly connected to the phrase structure, the dynamic shape and the melodic and rhythmic form, and that these parameters influence the amplitude of motion.

Medtner Sonata Reminiscenza. According to the pianists, the Sonata was performed with more hip and torso movements in passages that required playing a series of chords.

For them, larger movements from the forearms and elbows were needed for crescendos in this excerpt, while the hips were more implicated before accentuated chords or notes and for attacks.

Chopin 4th Ballade. Three pianists specified that it was difficult to exaggerate the expression in very energetic passages, since these moments already required an investment from the whole body. For instance, for the Ballade, pianists found that the polyrhythm between the hands and the fast displacements of the left hand made it difficult to exaggerate the performance. Many variations in tempo make it difficult to keep a stable rhythmical precision. One pianist mentioned that because of the figurations (i.e. short succession of notes) contained in the excerpt and the many repetitive patterns, special attention on the finger and hand movements was necessary.

Chopin Impromptu. Because of its rhythmic simplicity and uniform writing, most of the pianists found that the Impromptu was the easiest excerpt to perform in different expressive intentions. They also claimed that the expressive variations were mainly done in very melodic parts, which naturally induce larger amplitude of motion in an exaggerated performance. Three pianists specified that fluid and larger arm movements are often used in rubato sections. The moderate tempo of this excerpt therefore gives more flexibility in the movements.

- *Question 4.* Did playing in different expressive conditions affect any particular expressive parameters? If so, which ones?

Pianists revealed that playing in a deadpan manner affected their sense of phrasing and several other expressive parameters, such as tempo and dynamics. Five mentioned that they noticed that their tempo was faster and more stable. They reduced the rubatos, the variations in nuances, as well as the contrasts naturally present between the hands. These same parameters were accentuated in the exaggerated conditions. Four pianists noted that certain regions might have been emphasized, while other passages might have been disrupted by an exaggerated expression because this condition made it difficult to control the sound. Again, most pianists found it difficult to play in the immobile condition, saying that it prevented them from rendering the appropriate expressive result. They mentioned feeling rigid and tense, and as a consequence, they did not perform the dynamic contrasts as well as they would have wanted. On the other hand, one pianist noted that she had the impression that she could play more efficiently while still achieving similar or better sound results.

4.5 Discussion

This paper focused on the kinematic analysis of pianists' body movements in order to understand better how experienced pianists use body movements when performing different Romantic excerpts and when asked to play different performance conditions. We measured the duration and QoM of each performance and identified the regions in the score where pianists use common patterns of head movement.

Duration. We first looked at the variations in duration between the conditions for each excerpt. Although no distinct pattern was found among pianists regarding the overall duration of the performances of each expressive condition and excerpt, we found that the deadpan performances were generally played faster and the exaggerated performances slower as compared to the normal condition. Similarly to the results found in [232], and as post hoc pair-wise comparisons showed, the variation in duration between the deadpan and exaggerated conditions was only statistically significant in one measure of the Impromptu. The largest differences between the conditions in tempo were found in the deadpan condition for the Impromptu, whereas the smallest temporal deviations were found between the immobile and normal conditions, more specifically in the Ballade. This suggests that the restricted movement in the immobile condition did not affect the tempo as much as the level of expression in playing. From the questionnaire's results, pianists explained that when they were asked to reduce the level of expression, they used specific strategies, such as keeping a stable rhythm, removing the rubato and reducing the variations at the beginning and ending of phrases, whereas these same parameters were amplified in the exaggerated performances. As opposed to the results found in [252]'s study, the immobile conditions were not necessarily performed faster than the normal ones. This difference may be explained by the fact that the deadpan condition was not used in Wanderley's study. Therefore, the immobile condition, defined as performance with "little movement as possible" where no mention of expression was made could be interpreted differently in their study.

The similarity between the results of the present study, in which pianists performed three Romantic excerpts with contrasting difficulties and those found in [232], where pianists played one Chopin Prelude, indicates that the tempo is generally less affected by the QoM of movement used than by the level of expression regardless of the technical complexity of the piece. It is important to note that not all pianists varied the tempo in the same way to perform the excerpts and the conditions, suggesting that variations are the result of personal interpretative decisions.

Head QoM. Another purpose of the current study was to examine the effect of different pieces with various technical levels on pianist' head QoM and expression. By applying PCA on the pianists' position data, we showed that pianists' head QoM is an important parameter for communicating different expressions and the structural features of various excerpts from the Romantic period, which corroborates results from other studies (i.e. [28, 60, 175, 232]). All pianists performed all the excerpts with less head QoM in the deadpan and immobile conditions as compared to the normal one. Although no specific information as regard the movements was given to the participants for the deadpan condition, pianists considerably reduced their movement, as they did in the immobile condition, which is in agreement with results found in [61]. This indicates that playing in a deadpan manner may naturally restrict the movements and that movements are intrinsically connected to the expression of pianists. While the duration of the immobile condition was not affected as much as in the other conditions, the QoM, however, was affected in all the excerpts. Interestingly, the pianists used the same amount of head movement during the deadpan and immobile performance of the Impromptu and the Ballade, but not in the Sonata, for which less head QoM was used in the deadpan performance. This result is reinforced by the pianists' answers to the survey which state that remaining static during the immobile performance was facilitated by the fact that the technical challenges of the Sonata already limited the movements during a natural performance.

Davidson [61] found that pianists performed the exaggerated condition with more amplitude of motion. Although most pianists in this study also performed with more total QoM of the head in the exaggerated condition as compared to the other conditions, it was not the case for each pianist. For instance, the normal condition was performed with more QoM by one pianist in the Impromptu and by two pianists in the Ballade comparatively to the exaggerated condition. Although pianists still varied their movements in the exaggerated condition, the difference with the normal condition was not statistically significant. Since very few indications were given to pianists regarding the execution of the deadpan and the exaggerated conditions, some pianists may have been more reluctant to overly exaggerate the performance than to reduce its expression. As pianists observed in the survey, the technical complexity of the excerpt, such as in the Ballade, may have prevented them from performing with exaggeration without disrupting the flow of the performance.

Musical structure and motion recurrence. Similarly to [28, 157, 230, 232], we found that pianists' movements and expressive possibilities depend on the underlying structure of the excerpt, but also on its technical level. Variations in amplitude within the time-series of head position data between the conditions and the recurrent patterns in specific regions of the score suggest that certain movements are strongly associated with the structural features of the piece or with the physical constraints of the instrument. The Sonata, which contains more variations in sound dynamics and articulations than the two other excerpts, was performed with more accentuations in the exaggerated condition. Amplitude in head motion between conditions was significantly different in passages with ascending movements and crescendo dynamics. Recurrent head movements were observed when pianists performed wide arpeggios and passages with a chordal texture. Indeed, at certain moments the pianists' movements were dependent on the structure, which created postural constraints and resulted in body weight shifts to the extreme right for all pianists. On the other hand, the technical difficulty of the Ballade, attributed to the complex polyrhythm between the hands, the multiple chromatic passages, and the few moments of rest, prevented pianists from exaggerating the expression and the movements. Although reduced in the deadpan and immobile performances, the movement of the head was synchronized with the periodicity found in the rhythm in all conditions. Pianists moved in similar ways more often during the Ballade, which suggests that the technical level of this excerpt may require specific movements that leave less place for personal interpretative decisions. On the contrary, the Impromptu, characterized by a slow rhythm, smooth dynamics and articulations, gave the pianists the opportunity to emphasize different structural parameters when playing in different conditions. For the Impromptu, large difference in movements between the conditions were observed at the beginning of the melody of the main theme and at the repetition of the same theme, in the deadpan and immobile performances. The correlation map for this excerpt showed that only the beginning of the melodic theme and the end of the excerpt were marked with similar head movements. This means that pianists used distinct expressive movements to perform the conditions and express their personal musical ideas.

Survey. Pianists' answers to the questionnaire gave us important insights regarding the physical and acoustic strategies they can use to convey different levels of expression potentially associated with the musical structure. For most of the pianists, the arms movement and weight are considered as important motion cues to communicate their expressive ideas in a normal performance. Most of them found it difficult to exaggerate the performance in the Ballade, and found that performing in an immobile manner while trying to produce a normal expression was difficult for the Sonata and the Impromptu. For them, it was almost impossible to produce an accurate performance by restricting their movements the way they did.

4.5.1 Conclusion and further studies

This research provided new knowledge regarding the types of strategies pianists used to convey expressive intentions and structural parameters through body movements. Although pianists used varied strategies in terms of tempo and QoM to communicate different expressions, we identified similar trends in specific areas of the score. Our results indicated that when ten pianists performed three excerpts from the Romantic repertoire in difference expressive conditions (normal, deadpan, exaggerated and immobile): a) the duration of performances was less affected by the QoM used than the level of expression regardless of the technical level of the excerpt, b) the head QoM communicated well different expressions and structural features, and was only significantly different in the immobile and deadpan conditions when compared to the normal condition for all the excerpts, but mainly during the Impromptu, c) the Sonata allowed more variations in amplitude of the head movements in the exaggerated condition than the two other excerpts due to the variety of elements in the writing, whereas the complex polyrhythm and melody in the Ballade prevented pianists from performing with exaggeration in the movements, and d) recurrent head movements were found in specific regions of the score for the Sonata and the Ballade only. The results of this kinematic analysis, combined with common piano teaching methods, can benefit the field of piano pedagogy by helping teachers implement and integrate a more systematic approach in instrumental studio lessons in terms of accurate feedback related to movements and musical expression. Learners would be able to compare their movements to those of experienced pianists and become aware of the effect of that movement on the communication of expressive and structural parameters. Providing more systematic feedback in instrumental lessons can help students transfer teachers' explanations to various musical contexts so they may make independent creative choices, and aim to increase their musical communicative abilities.

Further studies investigating the ability of auditors to discriminate between a normal and immobile conditions could help evaluate whether reducing the movements in a performance affects auditors' perception of musical expression. The authors of this article have shown that even a slight modification in movements, such as the amplitude or acceleration of head motion can influence the sound parameters in a way that is noticeable for auditors [162]. Additional work is also needed to identify whether there are distinct groups of pianists who tend to perform with similar body movements and whether these groups differ in terms of individual musical formation, influences and pianistic styles. Extensions of this work could also consider the impact of pieces from various musical periods on pianists' movements. Finally, expressive parameters, such as loud sound dynamics, accents, fast rhythms and rich texture, can be heavily dependent on the motion coming from the hip region. Complementary studies may examine the co-variations between the force applied on the piano stool and body movements to understand further the mechanisms involve in the movements, as well as weight compensation strategies used by pianists.

Chapter 5

The Influence of Body Movements on Auditory Perception of Piano Performances

Abstract

Previous research focused on the cross-modal interactions between movement and sound in the perception of musical performance and the role of visual cues in auditors' emotional responses. Still, the effect of specific movement parameters on auditor perception and acoustic features needs to be investigated to understand better how auditors process acoustic cues in music performance. A first exploratory study was conducted to evaluate whether musically trained auditors are better at recognizing different performance conditions of 11 technical Romantic pieces when provided with one perceptual mode at a time (visual, auditory or both). The present study assessed how the performances of two pianists playing two excerpts with restrained body movements may influence auditors' perception in terms *of specific audio features, such as timing, phrasing, sound dynamic and articulation. We also evaluated how an immobile performance may affect these same parameters acoustically (key velocity, inter-onset interval (IOI), articulation). Results showed that auditors were better at discriminating between a natural performance and an immobile one for one of the two excerpts and pianists, but not both, and that they perceived variations in the phrasing of the performance and in sound dynamics. The acceleration of the head and torso was significantly different between the two conditions for both excerpts and pianists, who differed mainly in terms of quantity of motion (QoM), velocity and force. The immobile condition affected the key velocity and timing (IOI), but not articulation. The findings suggested that suppressing certain body movements can affect pianists' internal representation of the structural organization of the music, such as the timing and phrasing structure, as well as the sound dynamics.*

5.1 Introduction

The sensory interaction between auditory and visual information is known to influence listeners' expressive and cognitive judgments in music performance [33, 54], and convey important information with regard to phrasing [246] and timing [93, 105, 146, 262]. Many questions remain unanswered from these studies, such as how the quantity of movement influences the auditory perception of the overall performance, and how acoustic parameters are affected by a modification in physical movements. Although auditors' perception of expressive parameters conveyed through a reduced visual representation can be impressive (e.g. [61, 175]), we are still unsure which kinematic features influence auditory perception and in which musical contexts they do so. This information could be of great utility in music pedagogy to help students better judge how their movements are susceptible to affect the sound parameters of their performance in different musical styles, and more precisely which of these parameters need to be emphasized through body motion.

The influence of the auditory components that make up a musical performance have been extensively studied in music cognition research. Performers use a varied set of audio cues (e.g. tempo, articulation, timbre, phrasing) to convey diverse expressions, which are decoded by listeners when discriminating between different performance conditions [87, 133]. Kendall and Carterette [140] found that listeners, both musicians and non-musicians, were able to identify the expressive intentions (neutral, normal, exaggerated) of different instrumentalists through changes in timing and dynamics. However, although musicians and non-musicians have similar emotional reactions in response to a piece of music and make similar segmentation, judgement between musicians is more in agreement than between non-musicians [147, 222]. Listeners can notice changes in duration as little as 20 msec in isochronous sequences [40], but their ability to detect modulations in expressive timing are variable [199]. For instance, Repp [199] found that listeners perceive these timing variations better in the middle of phrases.

Sloboda [222] showed that musically trained listeners are more successful in identifying the variations in expressive features (timing, dynamics, articulation) when listening to more experienced performers than to the performances of less expert performers. Palmer [181] also found that chord asynchrony was used by expert pianists to make the melody perceptually salient for listeners. Indeed, rubato patterns were found mainly at phrase boundaries, as Clarke [42] found, with performers pausing or increasing the duration of events. Finally, overlaps, or the connection between a note offset and the subsequent one, were used to create perceptual continuity or discontinuity within a melodic line. In addition, listeners' emotional arousal ratings are more affected by contrasting phrases, and these responses are similar across structural levels such as sections, phrases and subphrases, suggesting a consistency between small and large timescales [154]. These results reflect the unconscious parsing of the musical structure, strongly linked to the expectations listeners have regarding the organization of a musical performance.

An important body of research in the past years was aimed at studying the relationships between different aspects of musical structure and expression (e.g. [40, 218, 222]). It has been shown that performers have practically complete control over timing, which refers to the temporal micro-variations of the underlying rhythmic structure [38], and to the expressive manipulations of the duration of the sound events [86]. Pianists appear to also modify articulation and note length depending on the metrical position of the note in the score [223]. Studies have shown that a performer can reproduce similar patterns of expressive timing over a long period of time [44] and in sight-reading as well [217]. Moreover, similar expressive timing profiles were observed between many different pianists when performing a piece by Schumann [198]. These findings suggest that, in addition to having a stable representation of musical structure, performers conceive the different structural levels of a piece in a similar way, and add their personal ideas by manipulating the finer details of structure. Indeed, Teixeira and colleagues [231] found that expressive timing manipulations and recurrent patterns of clarinet bell motion for different clarinet players occurred at specific moments in the score, such as melodic phrase endings and harmonic and dynamic transitions. Peaks of loudness manipulation happened at phrase endings, during passages marked with forte, which reveal the strong links between expressive acoustic patterns, the structure, and the recurrent movements of musicians.

Much research has been conducted on the role of visual feedback in the perception of musical performances. It has been shown that people can discern expressive intentions through performers' body movements alone. Johansson [129] was the first to use the point-light method[1] to reveal aspects of the perception of body motions. Even when a simplified body representation was displayed, observers were able to identify actions and intentions with lights, during gait [169] and knocking movements [193]. To pursue research on the perceptual influence of musicians' gestures on observers, several studies used different expressive conditions (normal, deadpan, exaggerated) combined with multimodal design. In these studies, the exaggerated condition is defined as a performance where musicians would exaggerate the acoustic parameters, whereas the deadpan condition refers to a performance with limited expressive content. So that additional features of the performance, such as facial expressions, would not influence the perception of the auditors by conveying emotional information, Davidson [61] used the same technique of point-light displays as Johansson. She found that auditors were better at identifying pianists' expressive intentions with visual information only than with vision and audio together, or audio only, and that the quantity and velocity of head and torso movement contain enough information to discriminate between performance conditions. Camurri and colleagues [28] found that key velocity and inter-onset intervals (IOIs)[2] in a pianist's performances of the Scriabin Etude varied the most between a normal and exaggerated performances. They found that velocity of head movement was positively correlated with key velocity and negatively with IOI. The effect of different visual conditions on auditors' ratings of audio parameters, such as phrasing, rubato and dynamic, has been examined by Juchniewicz [132]. The study included three conditions from all to no movement: full body movements, restricted head and facial movements, and no movement. While the audio was the same for all visual conditions, the 'full body movement' condition obtained the highest scores for each expressive parameter, followed by the 'head and facial only' condition, and the 'no movement' condition.

[1]Small light-emitting bulbs fixed to certain parts of the body.

[2]The time interval between the moment a note has been stroked and the moment the following note is played.

Furthermore, some evidence suggests that the expressive intentions conveyed through visual kinematic cues can have an impact on the subjective emotions perceived by auditors [34]. In different renditions of a marimba performance (no hands, torso or head only and full body), the movements of the head only appeared to contain sufficient information for observers to be able to recognize different emotions [52, 54]. Similarly, Nusseck and Wanderley [175] have indicated that freezing certain movements, from the torso or arms for instance, does not necessarily affect the expressiveness of clarinetists' performance, as observers' judgments of tension, intensity, and fluency of motion were similar to those of a performance where the movements were not altered. In Vines and colleagues' study [245], participants' emotional perception was not affected by clarinetists' level of expression in the audio modality, whereas the emotions were rated with significant differences for the visual condition.

While studying the effect of the interactions between visual and auditory information on the judgment of tension and phrasing in clarinet performances, Vines and colleagues [246] found that high tension was associated to fast, intense, and abrupt movements, whereas low tension was related to smooth and controlled motion patterns. Certain movements also helped anticipate the beginning of a new section, for instance when the performer initiates a breath while other movements may leave the impression that the phrase extends beyond the end of the note. Vuoskoski and colleagues [248] investigated the roles of visual and auditory cues in the subjective emotional reactions of auditors to understand the effect of pianists' body movements on the evaluation of specific auditory features. Results revealed that the conditions (normal, deadpan, exaggerated) elicited larger differences in the emotional ratings in the video-only mode than in the audio-only mode, but that both modalities had a significant effect on the emotional impact of the piano performances. The ratings of loudness and tempo variability obtained in the audio-only mode were significantly different between the performance conditions. However, the visual information had a cross-modal influence on the perception of loudness, but not on the perception of tempo variability.

While many studies report that expressive components of a performance may be perceived differently through visual and auditory observations, little has been done to identify precisely which body movements affect specific sound parameters. Moreover, the musical stimuli in these studies are often chosen arbitrarily and the results are not compared with a second piece, which makes it difficult to evaluate how one performer would react in different musical contexts. To our knowledge, no previous research has compared auditors' perception of acoustic features of performances in different conditions to the kinematic measurements obtained from the performances. In the present study, we seek to understand how a piano performance with restrained body movements, but natural expressive intentions, may influence auditors' perception of that performance.

A first exploratory study helped us choose which pieces to use for the current experiment from a set of 11 Romantic excerpts. The results from the exploratory study showed that auditors are able to differentiate pianists' expressive performances in the three modalities (i.e. audio-only, vision-only, audio-vision) but are generally better in the audio-visual modality. Certain pianists also modify their performance more than others depending on the expressive conditions. The current experiment examines both the perceptual and kinematic aspects of piano performances of three excerpts chosen from the 11 pieces used in the exploratory study. For the perceptual part, we investigate: 1) whether listeners are able to discriminate between an immobile and normal performances with auditory information only, and whether they can do so more easily for one particular pianist or excerpt; and 2) which audio parameters (i.e. timing, phrasing, sound dynamics, articulation) allow auditors to discriminate between the two performances. The quantitative analysis will help understand how body movements are used by different expert pianists and how they individually modulate different kinematic and kinetic parameters when asked to play in an immobile condition. The quantitative analysis of pianists' body movements and acoustic features serves to compare the results with auditors' perception.

We hypothesize that the immobile performance of pianists who naturally perform with a restricted amount of motion will be similar to a natural performance in terms of quantity, velocity and acceleration of movements. Similarly, the sound parameters will be less affected than for pianists who perform the two conditions with larger variations in body movements. This will be reflected in auditors' ability to discriminate aurally between a normal performance and an immobile performance. We also propose that the chosen excerpts will impact the pianists' possibility to contrast the sound and motion parameters.

5.2 Method

The current experiment is divided into two parts: 1) the perceptual evaluation by auditors, and 2) a comparison of the quantitative analysis of pianists' body movements and sound parameters of the performances.

5.2.1 Participants and musical tasks

In order to investigate the perception of auditors during performances with a natural amount of movements and with restrained body movements, we specifically chose to analyze the normal and immobile performances of two pianists.

Participants

Two pianists (1 female: 33 years old; and 1 male: 36 years old) participated in this study. These two pianists were selected from the study presented in [161] because they respectively obtained the smallest and largest differences between the performance conditions in terms of the total quantity of motion. Both pianists received their doctoral degree in piano performance from the Université de Montréal. Twenty-two auditors (average of 26.7 years old, SD=5.4, 7 females and 15 males) with at least five years of musical training participated to this study. The auditors were all undergraduate or graduate students (14 undergraduate and 8 graduate students) from McGill University in Montreal. All participants signed a consent form approved by the University ethics committee.

Choices of excerpts

The excerpts for the current study were selected from the exploratory study:

- **Pianist 1** Medtner Sonata Reminiscenza Op.38 (mes. 253-274)
- **Pianist 2** Chopin 4th Ballade (mes. 152-160)

5.2.2 Procedure

Pianists' measurements

Each excerpt was performed in two different conditions in this order: normal and immobile. The normal performances were played as naturally as possible, while during the immobile condition, pianists were asked to restrict their movements to the essential ones to produce an acceptable performance, as close as possible to a natural expressive sound. Pianists could choose the tempo they thought was appropriate to convey the expression of each condition. Performances were video recorded with a Sony Wide Angle video camera and audio recorded with a Sennheiser MKH microphone. Motion data were collected, at a rate of 240 frames per second, with a 17-camera Qualisys motion capture system, using 49 passive reflective markers put on the pianists' hands, elbows, shoulders, torso, head, and pelvis. The placement of markers on pianists' body is shown in Figure 5.1A. To perform the analysis and extract different kinematic parameters, a set of 16 markers was derived from the marker locations (Figure 5.1B). The midpoint of a joint was obtained by averaging the location of two or more markers using the MATLAB Motion Capture (MoCap) Toolbox [20]. Force applied on the stool was measured with a force plate positioned under it (Bertec FP-4060 force plate). Force data were acquired through the acquisition board of the Qualisys motion capture system. The beginning of each frame was time-stamped (SMPTE timecode) at 25 Hz, and a Rosendahl Nanosyncs HD word clock, sampled at 48 kHz, generated the clock signals for all the digital devices. The Rosendahl Nanosyncs was connected to the video camera, the Qualisys Sync Unit, and the RME Fireface audio interface. The Qualisys Sync Unit converted the SMPTE signals so that it may be recorded by the mocap cameras. The audio recording was slaved to the video signal. The control computer which recorded the audio and MIDI data from the MIDI keyboard with Reaper software was connected to the same network as the Qualisys computer. The Qualisys computer triggered, with OSC protocol, the recordings of both Qualisys Track Manager (QTM) and the audio and MIDI.

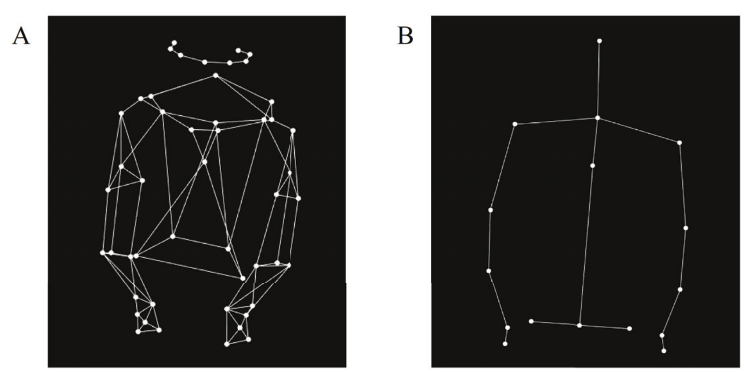

Fig. 5.1 **A** Anterior view of the location of markers attached to the pianists' upper body. **B** Anterior view of the joint representation of the pianists' upper body.

Auditors' perception

Auditors were asked to listen to 16 audio recordings of the performances. Each excerpt, the Ballade and the Sonata, were performed by two pianists, in two conditions, normal and immobile, for a total of eight recordings. The eight recordings were played to the auditors two times each to make sure that the discrimination was not due to chance. Auditors were asked to associate each excerpt to the appropriate condition. Then, they rated on a five-point scale: 1) their confidence level, and 2) the level of importance of specific acoustic features (i.e. timing, sound dynamics, phrasing and articulation) to associate the excerpts to the performance conditions.

5.3 Pianists' movement and audio data analysis

5.3.1 Audio analysis

First, we calculated the weighted average of auditors' correct responses per excerpt and pianist according to their level of confidence for each answer. To understand auditors' strategies to discriminate aurally between the conditions, four sound parameters were extracted from pianists' audio data for each excerpt: sound intensity, articulation ratio, note duration, and inter-onset interval (IOI).

Sound dynamic

MIDI key velocity (ranging from velocity 1 to 127) is an indication of the dynamic level or loudness of the sound [59] and is associated with the keypress of each individual note onset that is considered as a measure of sound dynamic.

Articulation

Articulation can be separated into two contrasting types, namely legato and staccato articulations. In a legato articulation, adjacent tones do not have perceptible break between them, with the sounding tone going on until the beginning of the next tone. Conversely, in a staccato articulation, the sound tone can be very short and is immediately followed by silence until the onset of the following tone [86]. Articulation can be defined as the ratio of tone duration to inter-onset interval (IOI) [78]. It refers to the amount of overlap between two consecutive notes belonging to the same melodic line. For instance, if one note ends exactly when the next note starts, the articulation ratio is 1, whereas when the note lasts for half the time between its onset and the onset of the following note, the articulation ratio is 0.5. Articulation in piano performance can be measured with the ratio of tone duration to IOI, with this simple calculation: $(offset_n - onset_n)/IOI_n$. With the midi data, the articulation ratio was first calculated for each single note in each hand separately.

Timing

To analyze expressive timing and phrasing, the duration of each note onset was extracted from MIDI data. For each hand, the tempo values were computed from the IOI, a good indicator of fluctuations in timing.

5.3.2 Movement analysis

We chose to measure three kinematic features (i.e. position, instantaneous velocity, and normal acceleration of specific body parts - head, torso, right and left elbows, right and left hands) and one kinetic feature derived from the force plate data (i.e. vertical force applied on the stool). We chose the normal acceleration because Caramiaux and colleagues [32] found that it presented the highest correlation means and was strongly associated to the loudness of a sound. These parameters give an effective spatial and dynamic representation of body movements and posture. In order to compare these movement features with the acoustic ones and to dissociate them from movement direction, we calculate vector norms for position, velocity and acceleration. The cumulative quantity of motion (QoM), instantaneous velocity and normal acceleration of each body part were measured from the joint location data, for each performance condition and each note.

5.3.3 Statistical analyses

To compare both pianists' performances, we measured the absolute percentage difference between the normal and immobile conditions for each movement and sound feature. The normal performances were taken as a reference point (0%) to compare against the values obtained in the immobile conditions. To investigate whether there are significant differences between the two performance conditions in terms of the kinematic and sound features and to understand the impact of movement on the expression, mixed-linear model analyses of variance were conducted for each musical excerpt, with the pianists taken as a random factor. Then, two-tailed t-tests were performed for each movement and sound features to identify for which of the pianists can we find these variations. We also verified what effect the musical structure had on pianists' movements for each condition. We averaged the values of each movement parameters for each phrase in each excerpt. A three-way ANOVA was run to examine the effect of pianist, expressive condition and phrase on the performance's movements and on acoustic parameters. In addition, a Tukey's Honest Significant Test (HSD) (with Bonferroni correction) was used to identify which groups of the factors - pianist, phrase, and condition - were significantly different. Finally, correlation analysis was performed to analyze the relationships between movement and acoustic features.

5.4 Results

5.4.1 Perceptual testing

First, we investigated auditors' ability to hear the potential acoustic differences between a natural performance and a performance where pianists are asked to play with only the essential movements needed to produce an acceptable performance. In average, participants associate the performances to the conditions with 62.35% of correct answers (SD=23.33, min=20%, max=100%), with certain auditors being better at recognizing the performance than others. However, there was no significant interaction effect found between the age, school degrees, as well as the style and years of musical training of participants. Figure 5.2 shows that overall the conditions are better recognized for the Sonata than for the Ballade, and for pianist 2 than for pianist 1 (weighted average=81.36% for pianist 1, and 95.38% for pianist 2). Pianist 1's normal and immobile performances of the Ballade are discriminated with a weighted average of 32.93%, whereas pianists 2's performances were better recognized with a weighted average of 83.58%.

Auditors then rated on a five-point scale the importance (i.e. not important to very important) of specific audio cues (phrasing, articulation, timing and sound dynamics) to associate the excerpts to the performance conditions. Figure 5.3 represents the frequency distribution of the auditors' ratings of each of these acoustic cues for the identification of the expressive conditions. The vertical line divides the "moderately important" responses in half. Each pianist was judged fairly similarly across the excerpts. For pianist 1, phrasing and timing were considered as the most important audio cues, rated respectively as 64.7% and 70.6% "very important" for the Ballade. For pianist 2, listeners also focused more on phrasing during both excerpts with 41.2% "very important" for both excerpts. However, according to listeners, sound dynamic was rated as more essential to discriminate between

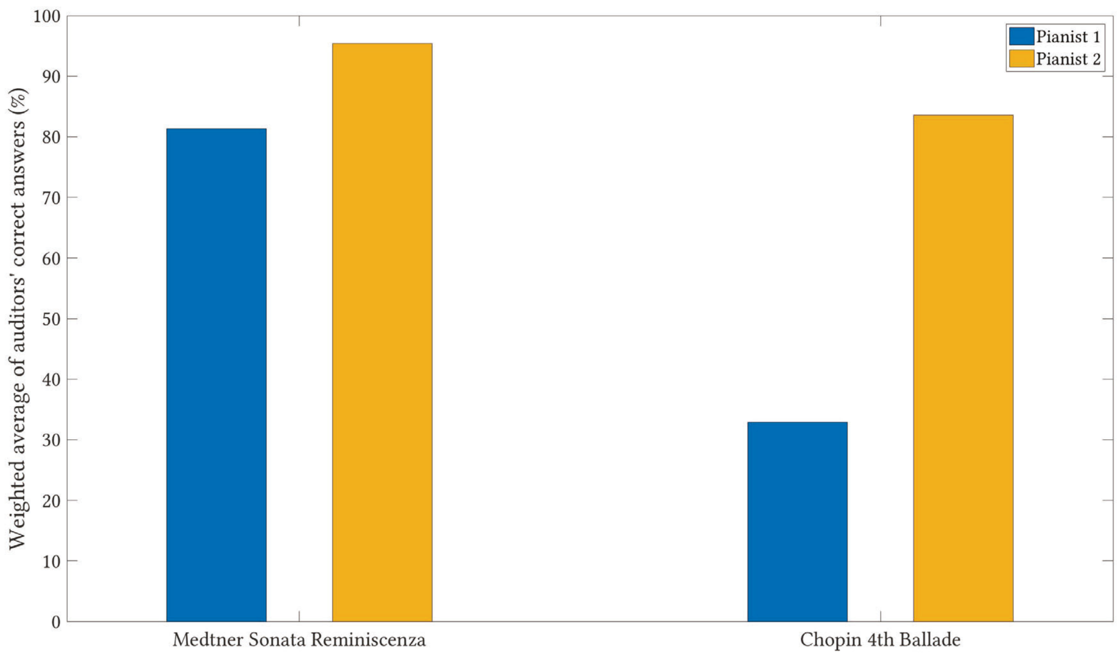

Fig. 5.2 Weighted average of auditors' good responses per excerpt and pianist

the two performance conditions mainly for pianist 2. These results indicate that both the pianist and the excerpt have an effect on auditors' ability to recognize the conditions. To further understand whether these results are influenced by body movements, the next section will discuss each pianist's kinematic and kinetic measurements for each condition and excerpt, and whether they had an impact on the acoustic features of the performances.

5.4.2 Pianists' movement and audio analysis

Inter-pianist differences

To analyze whether there are significant differences between the performance conditions for the movement and acoustic features, mixed-model analyses of variance were conducted for each parameter and excerpt (Table 5.1). The significance of the random intercept effects

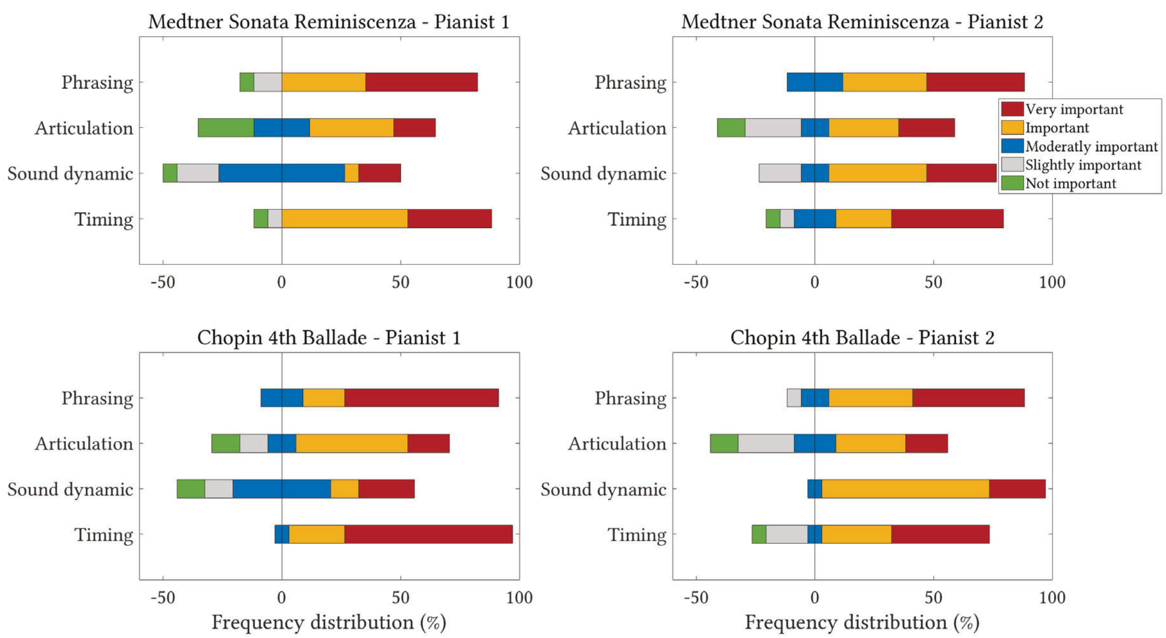

Fig. 5.3 Frequency distribution of auditors' answers on the importance of acoustic cues for condition identification

predicted for each pianist was evaluated using two-tailed t-tests. For the Sonata and the Ballade, only the sound dynamic (key velocity) was found to be significantly different ($p < .001$) between the two conditions for both pianists. Table 5.1 shows that this effect is more significant for pianist 2 than for pianist 1.

For the Sonata, all movement parameters are significantly different between the conditions for pianist 2 except for the hand acceleration. For pianist 1, only the acceleration of the head, torso and right elbow, as well as the left elbow velocity are significantly different. The use of force varies significantly for pianist 2 but not for pianist 1 whereas the opposite occurs during the performances of the Ballade.

For the Ballade, all movement features for the head and torso are statistically different between the conditions for both pianists. Elbow and hand velocity and acceleration vary significantly, while the QoM does not, except for pianist 2's right elbow. Pianist 1's normal and immobile performances of the Ballade differ significantly for more movement features than for the Sonata. Table 5.1 also shows that, for the Ballade, the acceleration of all body parts is significantly different between the conditions for both pianists.

Table 5.1 Mixed-model analyses of variance between the performance condition for each excerpt. * $p < 0.05$; ** $p < 0.01$; *** $p < .001$; n.s.: no significant effect.

		Medtner Sonata Reminiscenza	Chopin 4th Ballade
Acoustic features	**Sound dynamic**	$t(926) = -5.54$, $p < .001$ P1*, P2***	$t(686) = -4.46$, $p < .001$ P1*, P2***
	Duration	$t(926) = 1.77$, $p = .07$ n.s.	$t(686) = 0.09$, $p = .92$ n.s.
	Articulation ratio	$t(926) = 0.17$, $p = 0.86$ n.s.	$t(686) = -0.03$, $p = 0.73$ n.s.
	Timing (IOI)	$t(926) = 01.42$, $p = 0.15$ n.s.	$t(686) = 0.43$, $p = 0.66$ n.s.
Movement features	**Head**		
	-quantity	$t(926) = -4.41$, $p < .001$ P2***	$t(686) = -4.95$, $p < .001$ P1**, P2***
	-velocity	$t(926) = -12.65$, $p < .001$ P2***	$t(686) = -11.70$, $p < .001$ P1***, P2***
	-acceleration	$t(926) = -8.35$, $p < .001$ P1***, P2***	$t(686) = -10.24$, $p < .001$ P1***, P2***
	Torso		
	-quantity	$t(926) = -3.17$, $p = .002$ P2***	$t(686) = -4.82$, $p < .001$ P1**, P2***
	-velocity	$t(926) = -7.81$, $p < .001$ P2***	$t(686) = -8.67$, $p < .001$ P1***, P2***
	-acceleration	$t(926) = -7.95$, $p < .001$ P1**, P2***	$t(686) = -6.34$, $p < .001$ P1***, P2***
	Right elbow		
	-quantity	$t(926) = -3.23$, $p = .001$ P2***	$t(686) = -3.15$, p $= .002$ P2**
	-velocity	$t(926) = -5.99$, $p < .001$ P2***	$t(686) = -6.99$, $p < .001$ P1***, P2***
	-acceleration	$t(926) = -6.23$, $p < .001$ P1*, P2***	$t(686) = -6.26$, $p < .001$ P1**, P2***
	Left elbow		
	-quantity	$t(926) = -2.10$, $p = .04$ P2*	$t(686) = -0.57$, $p = 0.57$ n.s.
	-velocity	$t(926) = -6.10$, $p < .001$ P1**, P2***	$t(686) = -3.31$, $p < .001$ P1***
	-acceleration	$t(926) = -3.99$, $p < .001$ P2***	$t(686) = -3.93$, $p < .001$ P1***, P2*
	Right hand		
	-quantity	$t(926) = -1.93$, $p = .05$ P2*	$t(686) = -1.44$, $p = 0.15$ n.s.
	-velocity	$t(926) = -3.92$, $p < .001$ P2***	$t(686) = -3.01$, $p = 0.003$ P2**
	-acceleration	$t(926) = -1.81$, $p = .07$ n.s.	$t(686) = -5.61$, $p < .001$ P1*, P2***
	Left hand		
	-quantity	$t(926) = -2.05$, $p = 0.04$ P2*	$t(686) = -0.88$, $p = .38$ n.s.
	-velocity	$t(926) = -3.68$, $p < .001$ P2***	$t(686) = -0.90$, $p = .37$ n.s.
	-acceleration	$t(926) = -0.01$, $p = 0.99$ n.s.	$t(686) = -5.40$, $p < .001$ P1**, P2***
	Force	$t(926) = -4.90$, $p < .001$ P2***	$t(686) = -2.35$, $p = 0.02$ P1*

Sound parameters Figure 5.4 compares pianists 1 and 2 by considering the absolute difference between the normal and immobile conditions for each sound feature, where the normal condition is taken as the reference point. Both pianists performed each excerpts' immobile condition with a softer sound dynamic as compared to the normal performance. For the Sonata, pianists played the immobile condition with a slower tempo overall, a more legato articulation and a larger IOI than the normal performance. This effect is more pronounced for pianist 1 than for pianist 2, with a maximum difference of 12.4% for the duration. Pianist 1 played both excerpt with similar variations, whereas pianist 2 performed the Ballade' immobile condition faster and with a less legato articulation.

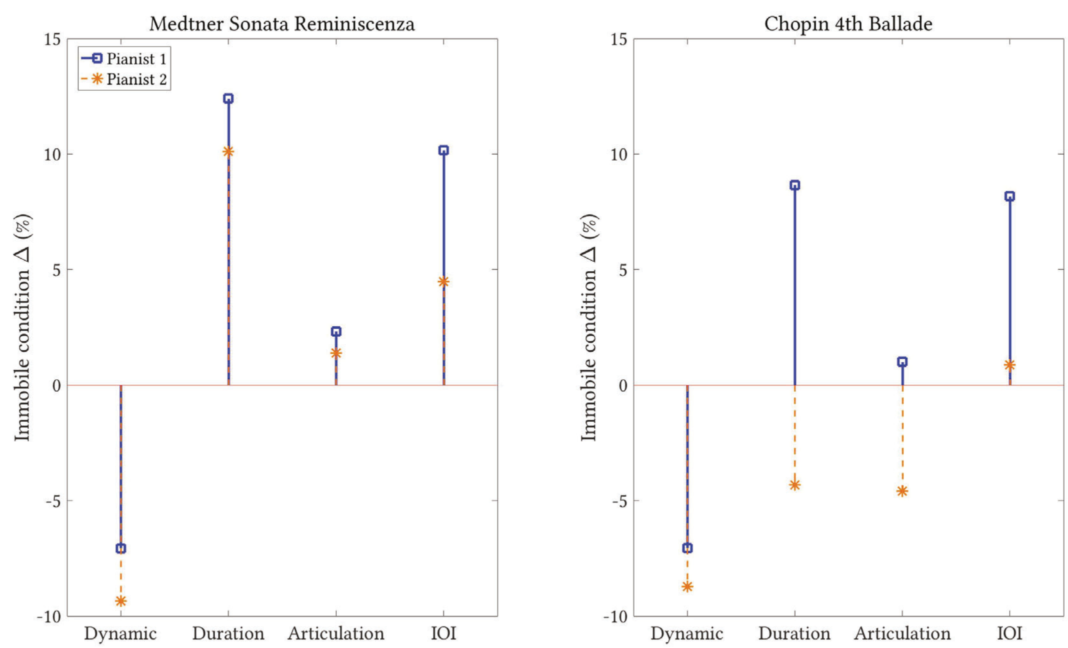

Fig. 5.4 Absolute difference for all acoustic features between the conditions. The line at zero represents the reference point, the normal condition, against which the immobile condition is compared.

Movement parameters The absolute difference for all movement features can be visualized in Figures 5.5 and 5.6 for the Sonata and the Ballade respectively. For the Sonata, all movement features differ substantially more from the normal performance in pianist

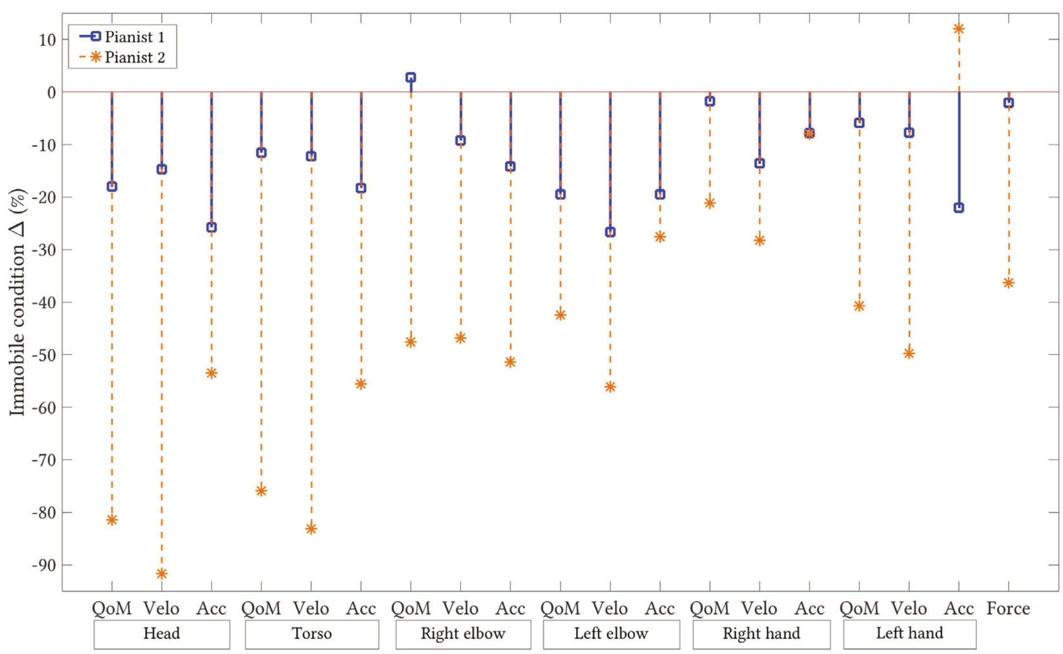

Fig. 5.5 Absolute difference for all movement features between the conditions for the Medtner Sonata Reminiscenza. The line at zero represents the reference point, the normal condition, against which the immobile condition is compared.

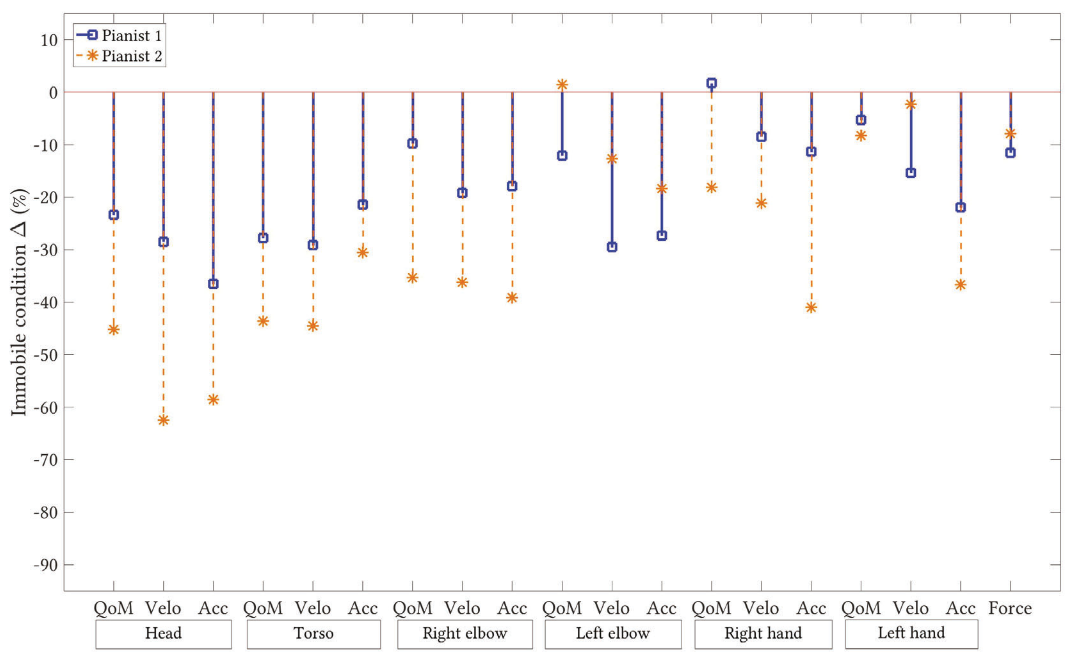

Fig. 5.6 Absolute difference for all movement features between the conditions for the Chopin 4th Ballade. The line at zero represents the reference point, the normal condition, against which the immobile condition is compared.

2's immobile performance than in pianist 1's, except for the right hand and left hand acceleration.

For pianist 1, the largest difference between the conditions is observed in the left elbow with 26.7% less velocity in the immobile condition. For the head, torso and elbows however, Figure 5.5 shows that changes in acceleration are more pronounced between the normal and immobile conditions than changes in QoM or velocity for pianist 1. Moreover, no other differences can be observed between the movement features for pianist 1's performance, contrarily to pianist 2, for whom the motion features of the head and torso are significantly more reduced than those of the hands. For the same pianist, the acceleration is less different than the QoM and velocity for all movement parameters, except for the right elbow, and the largest variation between the conditions is found in the head motion with 91.6% less velocity. It is interesting to note that the velocity and QoM vary the most between the conditions for pianist 2's head and torso movements, whereas it is the acceleration for pianist 1.

For the Ballade, the variations between the two conditions for both pianists are less pronounced than for the Sonata. The maximum percentage difference is still observed in pianist 2 with 62.5% less head velocity in the immobile condition (Figure 5.6). However, for this excerpt, pianist 1 performed the immobile condition with greater difference in force and left elbow and hand QoM, velocity and acceleration than pianist 2. We observe the opposite pattern for the right arm and hand.

Effect of musical structure on sound features

Since it has been shown that listeners do not necessarily rely on the degree of differences between note-by-note performance profiles, but rather on the grouping of meaningful segments in the music such as phrases, we investigated the relationships between the pianists, the conditions, and the phrasing structure for each excerpt. For each sound parameter, we averaged the variations per phrase and conducted a three-way ANOVA.

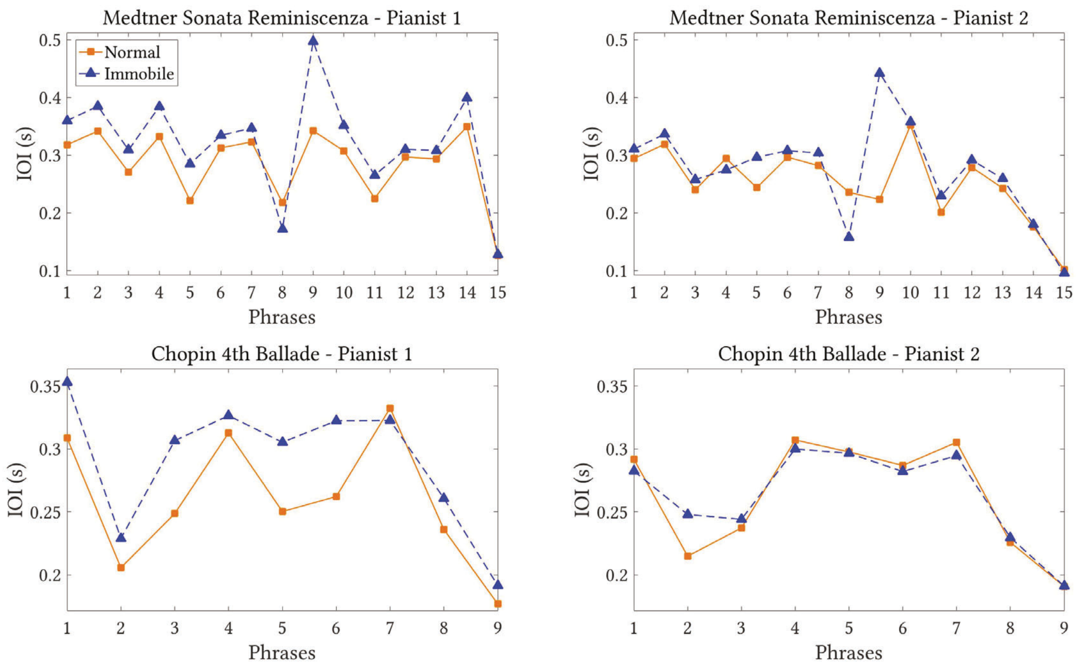

Fig. 5.7 IOI values for each phrase. The two upper graphs show the results obtained during the performances of the Medtner Sonata, and the two lower graphs displays the results of the Chopin 4th Ballade.

The results of the three-way ANOVA show that there is no significant main effect between the phrases and the conditions for all the parameters, except for the IOI during the performances of the Sonata. A Tukey's Honest Significant Test (HSD) with Bonferroni correction reveals that there is a significant effect at phrase 9 for both pianists [$t(60) =$ 4.14, $p < .001$], which coincides with a long ascending arpeggio movement, and at phrase 8 for pianist 2 [$t(60) =$ -2.38, $p = .02$], representing a series of accentuated chords (Figure 5.7). Although no particular regions are found significantly different between pianist 1's performances of the Ballade, we can still observe variations in timing at phrases 5 and 6 (a pause in the chromatic melody and a modulation of the main theme), whereas pianist 2' performances are fairly similar.

Figure 5.8 indicates how key velocity patterns are used for each pianist and excerpt. These patterns are trends, as no phrase has been identified as significantly different. Overall, pianist 2 plays with a louder sound dynamic for both excerpts during the normal performances, whereas the dynamic differs only in specific regions of the score for pianist 1. For the Sonata, this occurs toward the end of the excerpt, when performing two long arpeggios over five octaves. For the Ballade, pianist 1 performed phrases 5 and 6 with a louder dynamic, which coincide with the transition before the modulation and the re-exposition of the theme.

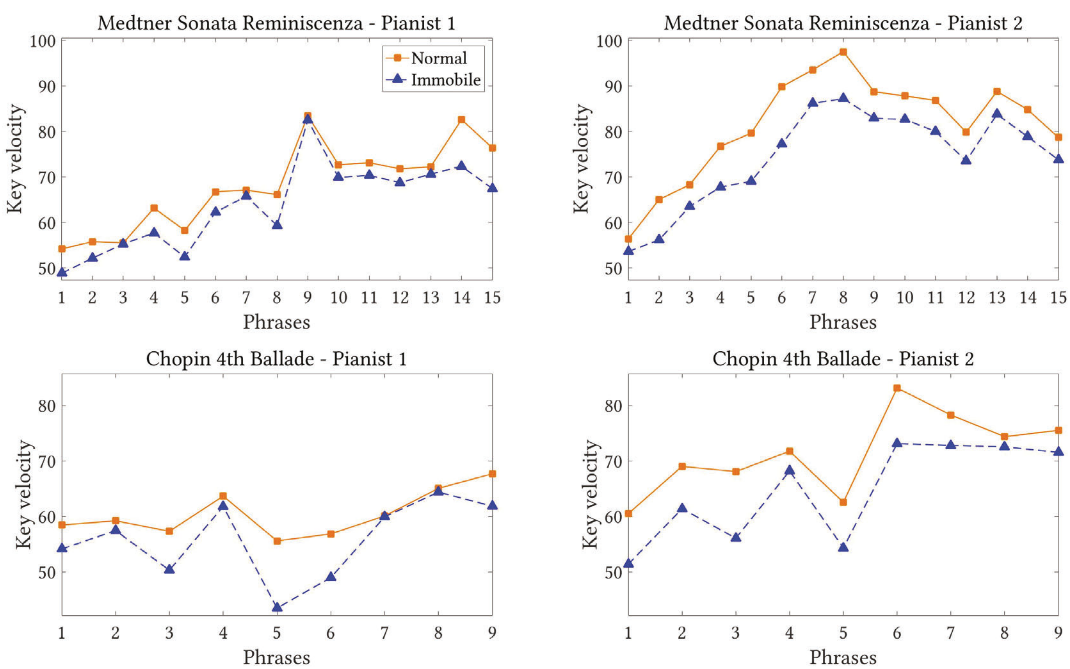

Fig. 5.8 Key velocity values for each phrase representing sound dynamics. The two upper graphs show the results obtained during the performances of the Medtner Sonata, and the two lower graphs displays the results of the Chopin 4th Ballade.

Relationships between body movements and acoustic parameters

We showed that key velocity for each note and IOI per phrase were statistically different between a normal and an immobile performance. Camurri and colleagues [28] found that peak-values for key velocity and IOI in piano performances were more correlated to head velocity when an analysis per segment (e.g. every two bars) was conducted. Therefore, we decided to correlate peak-values (maximum for key velocity and minimum for IOI with maximum head and torso movement features and force) for each phrase to assess how certain body parts, less implicated in the production of the sound, are linked to acoustic features. Results are shown in Table 5.2 for each pianist individually.

For the Sonata, head and torso QoM, velocity and acceleration, as well as force, are positively correlated to the key velocity values for both pianists. This means that a loud passage tends to be accompanied by large amplitude of motion, and great acceleration and force in the movements. Contrarily to the Sonata, head and torso velocity are negatively correlated to the key velocity in pianist 1's performance of the Ballade, suggesting that slower movements from the upper body are involved when the sound dynamic is higher. No correlation was found for pianist 2's performance of the Ballade.

Head and torso velocity are negatively correlated to the IOI for both pianists' performances of the Sonata, as well as the head and torso QoM and torso acceleration for pianist 2. For both pianists, the faster the movements, the shorter the duration between two consecutive note onsets is. For pianist 2, a larger amplitude of motion also seems to be related to a small IOI. Pianist 1's head acceleration correlates negatively to the IOI in the Ballade, whereas both pianists' torso velocity correlates positively to the IOI, but with a higher degree of correlation for pianist 2. The smaller the IOI, the slower the movements of the torso for the Ballade, whereas the opposite occurs for the Sonata.

Table 5.2 Results of the correlation between movement and acoustic features for both pianists. * $p < 0.05$; ** $p < 0.01$; *** $p < .001$.

		Pianist 1				Pianist 2	
		Medtner Sonata Reminiscenza				**Medtner Sonata Reminiscenza**	
		Sound dynamic (key velocity) Max	**Timing (IOI)**			**Sound dynamic (key velocity)** Max	**Timing (IOI)** Min
	QoM	**0.63***	-0.36		**QoM**	**0.52***	**-0.67****
Head	**Velocity**	**0.74****	**-0.66****	**Head**	**Velocity**	**0.72****	**-0.77*****
	Acceleration	0.25	-0.46		**Acceleration**	**0.67****	-0.44
	QoM	**0.65****	-0.37		**QoM**	**0.51***	**-0.64****
Torso	**Velocity**	**0.65****	**-0.65****	**Torso**	**Velocity**	**0.76****	**-0.85*****
	Acceleration	**0.54***	-0.34		**Acceleration**	**0.74****	**-0.78*****
	Force	**0.67****	**-0.55***		**Force**	**0.70****	-0.30
		Chopin 4th Ballade				**Chopin 4th Ballade**	
		Sound dynamic (key velocity) Max	**Timing (IOI)** Min			**Sound dynamic (key velocity)** Max	**Timing (IOI)** Min
	QoM	-0.45	0.31		**QoM**	0.02	0.36
Head	**Velocity**	**-0.66***	0.31	**Head**	**Velocity**	0.33	0.52
	Acceleration	0.37	**-0.73***		**Acceleration**	0.55	0.08
	QoM	-0.25	0.21		**QoM**	-0.10	0.31
Torso	**Velocity**	**-0.76***	0.36	**Torso**	**Velocity**	0.23	**0.67***
	Acceleration	0.01	-0.61		**Acceleration**	0.12	-0.02
	Force	-0.06	0.16		**Force**	0.49	0.41

5.5 Discussion

Although previous studies have shown that visual information contained in a musical performance can influence the perception of different expressions more than audio information alone (e.g. [34, 54, 61, 245, 248]), they have not evaluated the effect size that body movements have on that of auditory performance cues.

Perceptual study Results from the perceptual test indicate that auditors are better at discriminating aurally between the normal and immobile performances of the Sonata than of the Ballade, and have performed above chances when listening to pianist 2's performances, but not necessarily for pianist 1. These findings partially contradict Vines and colleagues' results [245], in that the auditors of our study were able to perceive acoustic differences between a normal condition and an immobile condition even while listening to a performance for which the movements were reduced. Similarly to the ones of Koren and Gingras [146], our results revealed that the excerpt may affect auditors' ability to discriminate between a natural performance and a performance with limited amount of movements, but also that the immobile condition may impact more some of the distinctive features for one performer than for another. In order to understand better why a specific piece or pianist makes it possible to recognize a performance condition, we analyzed pianists' individual differences in terms of their use of body movements when asked to perform in an immobile manner, while maintaining a natural level of expression. To compare auditors' results with pianists' quantitative measurements, we examined the effect of modifying body movements on sound features.

Movement parameters We observed that the head and torso acceleration is an essential parameter to describe the different ways of playing in a normal or immobile condition for both pianists and excerpts, which is in line with earlier results [54, 61, 196]. However, there were still divergences between pianists.

Pianist 2 reduced significantly the QoM from the upper body, arms and hands for the Sonata, whereas pianist 1 did not. In spite of this, listeners were able to distinguish between the conditions for both pianists. The fact that pianist 1's amplitude of upper body movements in a normal performance was already small could explain that the difference between the two performances was limited to a change in acceleration for certain body parts. However, although most of pianist 1's movement features during the Sonata were not found statistically different between the conditions, listeners were still able to make the distinction between them. This tells us that even when the movements are slightly reduced as compared to a normal performance, certain sound parameters such as the sound dynamic and expressive timing of phrases can be impacted enough to be perceptible for listeners.

For the Ballade, pianists altered the movements of the hands and arms during the immobile performance in very different ways that suggest that pianist 2's expressive movements were focused on the melody at the right hand, whereas pianist 1's left hand expressive movements support the constant rhythmic pattern.

The fact that the two pieces selected for this experiment differed substantially in terms of rhythmic structure, sound dynamic, texture and articulation, can explain why the performances from the Sonata might be easier to discriminate. The greater distinctiveness of the Sonata fragment - with its textural and rhythmic variations, which may require more movements from the whole body - could explain the difference in the accuracy of discrimination between both pieces. As found Koren and Gingras [146], we have demonstrated that even a slight modification in the movements normally used to perform a complex excerpt such as the Sonata, may affect the sound in a more noticeable way than for an excerpt with simpler requirements such as the Ballade excerpt.

Sound parameters We showed that the sound dynamic was significantly different between the conditions for the Sonata when looking at individual note profile, and that this was the case for both pianists, but more specifically for pianist 2. This is similar to Camurri and colleagues' results [28] showing that key velocity (or sound intensity) varied the most between the expressive performances of a pianist. Each entire excerpt was performed louder by pianist 2 during a normal performance. In Koren and Gingras's study [146], listeners found difficult to focus on audio parameters such as dynamics to compare across different pieces and did not rely on note-by-note patterns during the sorting task. Contrarily to their findings, the auditors of our study rated the sound dynamic almost as equally important as timing for the Sonata, and as the most important audio cue for pianist 2's performance of the Ballade. However, no significant difference was observed when the key velocity values were averaged per phrase.

A different scenario occurs for the timing (IOI), where grouping the values per phrase generated significant differences between the conditions in certain areas of the score, namely loud accentuated chords and long arpeggio passages. Similarly, previous studies have shown that listeners were good at capturing subtle changes in timing [40], and these changes were perceptually more salient at phrase boundaries [42]. Our results may explain why listeners have perceived the expressive timing variations between the conditions by focusing on the expressive timing per phrase. Indeed, timing and phrasing were used prominently by listeners for both pianists to discriminate between the performances, which supports earlier results from studies that evaluated listeners' ability to sort musical performances [92, 146, 203, 246]. This suggests that, in order to capture the differences between two pieces or performers, listeners may rely on a more global impression of timing, such as variations that occur at phrasing boundaries. In addition to varying the sound dynamic during the immobile performance of the Sonata, both pianists also modified the timing of phrases, but not necessarily as a consequence of reducing significantly the amplitude of body movements.

For none of the pianists were the articulation and duration of each note onset found statistically different between the performance conditions. Contrarily to Gingras and colleagues [92] who found that listeners recognized different performances of the same piece as being played by the same performer based on tempo and articulation, auditors in this study did not rely on articulation to discriminate between performance conditions. This indicates that when pianists reduce the QoM, the articulation is not as affected as the sound dynamic or the timing. These results suggest that auditors' attention was brought towards the variations in phrasing and timing for both excerpts and pianists rather than on the differences in articulation, and that the perception of sound dynamic was specific to pianist 2's performances of the Ballade.

The fact that listeners were better at identifying correctly the conditions for pianist 2's performances of the Ballade than those of pianist 1 can be explained by the larger variations in sound dynamic, which in turn was affected by the substantial fluctuations in body movements of the upper body. This seems to indicate the importance that body parts further away from the keyboard, such as the head and torso, plays in the overall expressive results. Moreover, although less significant for pianist 2, there were differences in IOI and sound dynamics between pianist 1's performances of the Ballade. Other factors could explain why auditors could not distinguish between the normal performance and the immobile one. For instance, although both performance were different, they might have been stylistically appropriate and pleasant to hear. The results also reveal how individual pianist rely on different body movements to communicate expressive ideas and the structural parameters. Even small changes in amplitude of motion can affect significantly the acceleration of movements, which may drive pianists outside their comfort zone and entail important changes in the overall expressive result.

Correlation analysis With correlation analysis, we verified whether certain movement features were associated to sound parameter. Camurri and colleagues [28] found that key velocity and head velocity were positively correlated, whereas IOI was negatively correlated with key velocity. For Romantic pieces with a more dynamic and varying rhythm such as the Sonata, we also found that a small IOI is related to larger head and torso QoM and faster movements. The great fluctuations in sound dynamics throughout the excerpt also contribute to large head and torso amplitude, velocity and acceleration of motion. However, the Ballade excerpt is rather constant in terms of sound dynamic and rhythmic structure, but contrarily to the Sonata, its complex polyphonic rhythm may limit pianists' upper body movements. Therefore, for this excerpt, the upper body movements tend to be slower as the sound dynamic increases.

5.6 Conclusion

The present study investigated the ability of experienced listeners to accurately discriminate aurally between two performance conditions, normal and immobile, when different pianists perform two excerpts from the Romantic repertoire. This research helped clarify the relationships between pianists' expressive communication in Romantic piano repertoire and auditors' perception of expressive parameters. Few studies have evaluated the ability of humans to process acoustic cues in music performance. To our knowledge, the present research is the first empirical study that examines the listeners' ability to accurately discriminate between performance conditions. We highlighted the fact that the piece performed may exert an influence on the body movements required to play with the desired musical expression. Our results also indicate that movements that are less central to the production of the sound, such as head and torso movements, can impact how expressive parameters, such as sound dynamic and timing variations, are perceived.

Because of the small sample size used in this study – both pianists and auditors - the results only allow plausible interpretations. In addition, although this study showed that a pianist's performance could be discriminated on the basis of changes in sound features entailed by a small modification in amplitude of body motion, more research is needed to understand how different levels of musical expression in pianists' performance, for instance an exaggerated level of expression and natural body movements, would affect auditors' visual perception. Further studies could investigate whether acceleration of movements in expert piano performance can provide sufficient information to differentiate both performance conditions for different musical excerpts. This would help clarify which structural parameters affect this variation in acceleration. It could also be interesting to analyze the effect of an immobile performance on the auditory perception of musical expression through continuous ratings (e.g. [154, 155, 246]) and evaluate various parameters such as appropriateness, phrasing structure and sound dynamics. The analysis of auditory perception through performance conditions can help researchers understand the relationships between body movements and sound. This information could be used to design new pedagogical tools to help students grasp the link between their movements and the desired level of expression and anticipate how auditors would react to their performance.

Chapter 6

Pianists' Postural Sway while Playing Romantic Pieces in Different Performance Conditions

Abstract

Although the relationships between pianists' swaying movements and musical expression and structure have been previously examined, the biomechanics of the upper-body movements in piano performance remains largely unexplored. This study investigated the kinetics of three Romantic piano performances, with motion capture and force plate technologies, while experienced pianists play in different expressive conditions. We assessed the influence of body movements and expression on pianists' postural sway by measuring specific postural angles, as well as kinetic variables derived from the force plate data, such as vertical force, centre of pressure (COP) displacements and velocity of the displacement. Results showed that pianists can stabilize their posture when body movements are restrained, as the COP

displacements remained similar to the ones adopted in a natural performance. However, when performing two of the excerpts with and exaggerated expression, the displacements of the COP and their velocity increased. Moreover, the upper body angles along the anterior-posterior (AP) direction correlated strongly with the use of vertical force, especially for the Medtner Sonata excerpt. We also found that the medial-lateral (ML) COP displacement, the vertical force and the COP displacement velocity varied significantly between all the excerpts, which suggests that pianists use kinetic parameters with precise control to perform the structural features of each musical excerpt. Disrupting the natural expression and posture a pianist chooses for performing a particular piece can be detrimental to the fluidity and musicality of the performance, and more so for pieces that require a more advanced technical ability.

6.1 Introduction

Most of the instrumental pedagogues share the same goals of teaching students to play expressively, by adopting a healthy and adequate posture [258, 267]. However, conflicting views and methods in piano teaching can be a significant source of confusion for students learning how to approach the physical aspect of piano performance. Music pedagogy has suffered from a lack of explicit theories on how expression [137] and posture [211] are taught, which explains why teachers encounter difficulties while attempting to provide consistent and accurate information to students in that regard. Piano teaching would benefit from the inclusion of a science-based pedagogical approach that takes into consideration the analysis of kinematic (i.e. posture) and kinetic (i.e. forces) aspects of musical performance in relation to the musical structure and expression. Despite the fact that research has been done on the biomechanics of fingers, hands and arms to understand the impact of piano technique on the control of touch (e.g. [103, 178]), and on how to reduce hand and upper-limb injuries (e.g. [83, 212]), there is still a lack of knowledge about postural control and its link with musical expression in the piano pedagogical literature. Incorporating a more scientific perspective in piano pedagogy could lead to the development of improved teaching methods that would help student-pianists increase their musical communication abilities through a better understanding of body posture.

Postural control is defined as the ability to balance the body in space through visual, vestibular, and proprioceptive systems, and neuromuscular responses [69]. To quantify postural sway and stability in different conditions (i.e. sitting or standing position, disturbed or undisturbed settings), the center of pressure (COP) is often used in posturography [194]. The COP represents the average resulting forces distributed over an area of the body in contact with the ground, such as the feet, and can be measured by a force transducer (i.e. force plate) [265]. It also reflects the force and movements applied on the force plate rather than the amplitude of motion. Different measures can be extracted from the COP to characterize postural sway (e.g. [72, 266]), but the most common ones used are COP displacement, mean velocity of COP displacement, and frequency variables, such as the spectrum of postural oscillations. For instance, it was shown that large deviations in magnitude and direction of the COP behavior indicate greater postural instability [205]. The total sway path of the COP was reported as a reliable measure to expose the variances across different groups of individuals (i.e. normal, parkinsonian patients, and osteoporotic patients) [8], whereas the mean velocity of the COP displacements proved to be useful in estimating the consistency within different groups of participants performing quiet upright stance [48, 153]. Moreover, to study the role of sound in motion on participants' postural control and oscillations of body movements while standing, the velocity and entropy of the

COP displacements[1] were shown to vary according to participants' focus of their attention and to the cognitive task performed [90].

Studies conducted on the posture of musicians generally focus on playing-related musculoskeletal disorders (PMRDs) and health problems [261, 270]. In piano performance, the effect of posture can have a major influence on the amount of muscular effort needed to play. For instance, a forward head posture has been shown to be responsible for chronic neck pain [118]. In a seated position, kyphosis of the thoracic spine (i.e. excessive convex curvature and rounded shoulders) and lumbar lordosis (i.e. forward tilt of the pelvis) can create muscular tension because the center of mass of the upper body is pushed forward or backward [136]. A straight spine fully erect with the pelvis in equilibrium minimizes the muscular effort needed to maintain the posture. Moreover, postural stability may be affected when pianists use their feet for pedaling [16]. To increase kinesthetic awareness and trunk and pelvic stability during performance, many musicians have turned to somatic training techniques, such as the Feldenkrais method or the Alexander Technique. Along with helping develop a healthy playing technique and avoid potentially harmful movements, these methods can equip musicians with detailed knowledge of the body's structure and functions [46, 225]. Piano pedagogical methods also advocate that the movements of the upper body should be led by the head, then distributed to the other vertebrae, which would send the weight to the pelvis [160].

Recent studies have combined kinetic and kinematic analyses on pianists' upper-limbs to understand better the organization of multi-joint movements during fine motor actions and to characterize the types of touch (see review by Furuya and Altenmüller [79]). Furuya and colleagues [84] found that pianists use gravity to accelerate elbow extension during keystroke, and this effect is intensified for louder tones. Moreover, the velocity and muscle

[1] A measure of the regularity of the COP displacements.

activity of the shoulder, wrist and finger movements increase with tempo and louder tones, whereas the elbow velocity decreases [81, 82]. A pressed touch was also characterized by a less abrupt initial force, and a travel time considerably longer than the struck touch, indicating precise control of finger-tip movements, intensity and tone onset [103, 144].

In music performance, the instrument being played influences the biomechanical and expressive interactions. For instance, a seating position restricts the posture and expressive movements, which are mainly localized to the upper body. To study how pianists' sway relates to expression and musical structure, various experimental conditions have been used in previous research. Shoda and Adashi [220] investigated the relationships between a pianist's postural angles and expressive manipulations of a performance through different conditions (deadpan, artistic, exaggerated). In the exaggerated condition, the acoustic parameters were played with exaggeration, whereas the deadpan condition referred to a performance with limited expressive content. The pianist highlighted specific structural elements in each piece performed (Chopin Prelude and Etude), such as phrase boundaries or thematic presentation. Cross-correlation analyses revealed that temporal deviations were related to changes in body angles in a fast piece with a constant rhythm. Clarke [40] found that temporal organization of music can be perceived in pianists' body sway, and that a clear periodic movement can be associated to a specific musical context and rhythmic structure [157]. In addition, pianists' head and torso tilt has also been shown to accentuate certain points in the melody [126]. However, it was shown that the rocking movements is not strictly connected to the musical structure, but also to the performer's individual expressive reaction to the music [64].

As for other instruments, Dalca and colleagues [55] found that in an exaggerated performance, clarinetists' oscillating movements of the upper body augmented as compared to a standard condition, especially at phrasing boundaries, and that for the same performer, exaggerated performances were more consistent across time. More closely related to this study, kinematic and kinetic measurements were combined with performance conditions (normal, static mental, static chest and static chest and head) to study cellists' postures [210]. In a condition where the movements of the head and trunk were immobilized with a harness, the COP displacements were larger than those of a natural performance. For the same condition, it appeared that cellists' torso was forced to move at the same velocity as the bow strokes, which resulted in greater force variations and larger COP displacements. These results are in accordance with Adkin and colleagues [1], who proposed that a greater control of posture is related to a diminution in postural sway or COP displacements.

Although studies have previously examined the relationship between pianists' postural sway and expression, as well as kinematics and kinetics of upper-limb movements, little is known about how expert pianists adjust their posture and kinetic parameters in relation to expression and different musical excerpts. The main purpose of the present study is to investigate the relationships between kinematic and kinetic aspects of piano performances to understand better pianists' postural sway in different musical contexts. We also evaluate the effect of various expressive conditions and Romantic excerpts on the degree of variations in pianists' upper body postural movements. We hypothesized that certain kinetic features, such as vertical force and COP displacements, will be more strongly correlated with the head and torso postural angles than with the hip angles, and that this relationship will be accentuated by the type of excerpt being performed and its respective structural parameters. For instance, a piece with large variations in rhythm and articulation such as the Sonata will entail a strong correlation between kinetic and kinematic features, and that different levels of expression will have little effect on this relationship and on pianists' postural sway. We also suggest that a voluntary immobilization of the movements will occasion a disconnection between expression and posture, and therefore, will minimize the relationship between the movement kinematics and kinetics for all the excerpts.

6.2 Method

6.2.1 Participants and musical tasks

Participants Ten pianists participated in this study (M=29.6 years old, SD=5.8 years old, 6 Female 4 Male). The participants were undergraduate, graduate or post-graduate students (3 doctoral, 3 master's, and 4 bachelor's degrees). All participants signed a consent form approved by the university ethics committee.

Choices of excerpt In a previous exploratory study, we investigated the relationships between pianists' use of motion cues (i.e. quantity of motion (QoM) and force applied on the stool) and sound parameters that convey expression and information about the structural parameters of music. Eleven pianists performed different Romantic excerpts three times in the following order: normal, deadpan, exaggerated and immobile conditions, for a total of 12 performances per pianist. The deadpan condition was described as playing with a reduced level of expression, whereas the exaggerated one, as playing with an exaggerated level of expression [60]. In an immobile performance, pianists were asked to consciously reduce their movements as much as possible without sacrificing the expression in their play [232, 251]. The quantitative analysis showed interesting comparative results between the compositional structure and the pianists' gestural language for three of the 11 pieces, which were also contrasted in terms of structural parameters and technical difficulty. The results from this study are summarized in [161] and the same three excerpts were chosen for the current experiment:

- Medtner Sonata Reminiscenza Op.38 (mes. 253-274) (referred to as The Sonata)

- Chopin 4th Ballade (mes. 152-160) (referred to as The Ballade)
- Chopin Impromptu (mes. 43-51) (referred to as The Impromptu)

Each excerpt was performed in the same four expressive conditions as in the exploratory study. The pianists played each excerpt once in each expressive condition. Participants could choose the tempo they found appropriate to convey the expressive conditions. The order of excerpts was randomized for each participant, and the conditions were performed in the same order (i.e. normal, deadpan, exaggerated, immobile).

6.2.2 Measurements

Pianists' movements were acquired with a 17-camera Qualisys motion capture system. Force applied on the piano stool was measured with a Bertec FP-4060 force plate positioned under it through a USB-2533 analog acquisition board, which was connected to the Qualisys Sync Unit. Performances were video recorded with a Sony PMW-EX3 Wide Angle video camera and audio recorded with a Sennheiser MKH-8040 microphone. A Rosendahl Nanosyncs HD word clock, sampled at 48 kHz, generated the clock signals for all the digital devices (video camera, Qualisys Sync Unit, and Fireface audio interface), and provided a SMPTE timecode sampled at 25 Hz to time stamp the beginning of each measurement. The audio recording was slaved to the video signal receiving the SMPTE signal from the word clock. The control computer recorded the audio and MIDI from the MIDI keyboard with Reaper software and was connected to the same network as the Qualisys computer. QTM triggered the recordings of the mocap data and the audio and MIDI data from the keyboard using the OSC protocol.

6.2.3 Data analysis

Kinematic data

Head, torso and hip angles have been shown to characterize postural control in different sitting conditions [177]. A three-dimensional coordinate system was used as a reference to measure these specific postural angles along the medial-lateral direction (ML) (along the keyboard) and anterior-posterior direction (AP) (towards and away from the keyboard). Each segment of interest was measured in relation to a central point in the body, that is the middle point between the right and left hip markers, respectively named RPSIS and LPSIS. The angles and markers can be visualized in Figure 6.1. The following were measured:

- **Head**: ML and AP angles in degrees of the segment between the head marker (H4) and the middle point between RPSIS and LPSIS (Hip Mid).
- **Torso:** ML and AP angles in degrees of the segment between the trunk marker (STRN) and the middle point between RPSIS and LPSIS (Hip Mid).
- **Hip:** ML and AP angles in degrees of the segment between the right hip marker (RPSIS) and the middle point between RPSIS and LPSIS (Hip Mid).

The angles were computed with the following equations:

$$\theta_{head} = arctan\frac{\sqrt{y_{head}^2 + z_{head}^2}}{x_{head}} \tag{6.1}$$

$$\alpha_{head} = arctan\frac{\sqrt{z_{head}^2 + x_{head}^2}}{y_{head}} \tag{6.2}$$

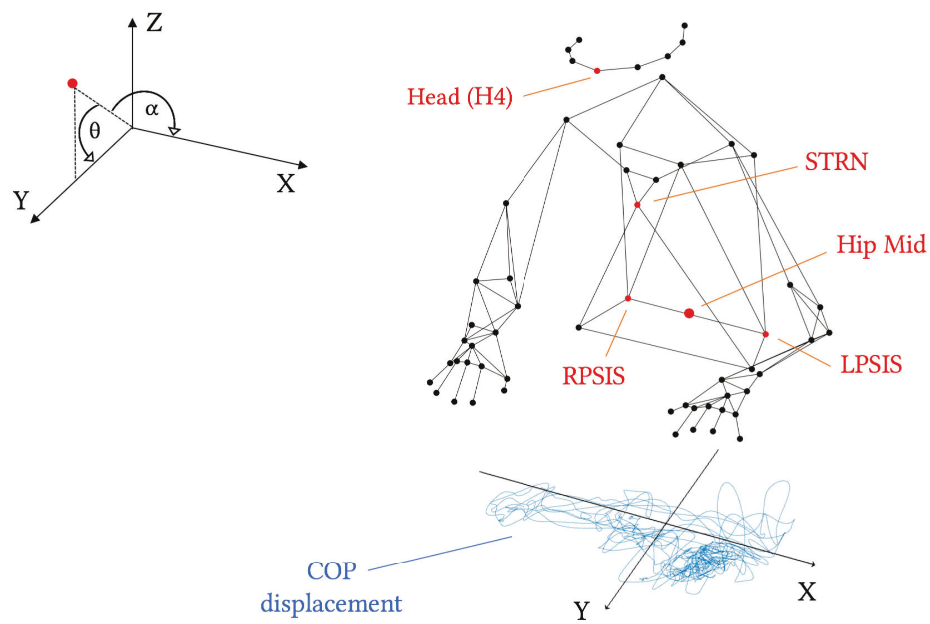

Fig. 6.1 Marker placement and the six postural angles of interest denoted by the markers H4 (head), STRN (sternum), RPSIS (right posterior superior iliac spine), LPSIS (left posterior superior iliac spine). The blue line represents the COP displacement on the force plate. A three-dimensional coordinate system was used as a reference to measure the angles of interest: α, which corresponds to the angle in the ML direction (along the keyboard), and θ, corresponding to the angle in the AP direction (towards and away from the keyboard).

Kinetic data

The ground reaction force vector over time[2], as well as the COP XY displacements, explain well the nature of body sway, and have been shown to be reliable measures of postural stability [141, 171, 197]. It was also shown that the AP and ML components of the COP display different patterns of postural behavior [264]. For our study, the following kinetic parameters were measured to quantify pianists' body sway:

- Vertical force
- ML and AP COP displacements
- Velocity of the COP displacement (Vd)

Kinetic variables were extracted from the forces and moments (torques) data obtained from the force plate (Figure 6.2). The force plate, equipped with four strain gage transducers, is designed to measure the three forces (F_x, F_y, F_z) and moments (M_x, M_y, M_z) exercised along the three perpendicular axes by the person who stands or sits on it. From the forces and moments, we can calculate the x position (Equation 6.3) and y position (Equation 6.4) of the COP:

$$x_{COP} = \frac{M_y}{F_z} \qquad (6.3) \qquad\qquad y_{COP} = \frac{-M_x}{F_x} \qquad (6.4)$$

Force measurements were filtered with a 2nd-order lowpass Butterworth filter with a cut-off frequency of 10 Hz [90]. The displacement velocity (Vd) was obtained by dividing the change in displacement by the change in time (Equation 6.5):

[2] The force exerted on a body in direct contact with the ground. When a person stands still, this force is equal to the person's weight multiplied by the gravitational acceleration ($F = m \times g$).

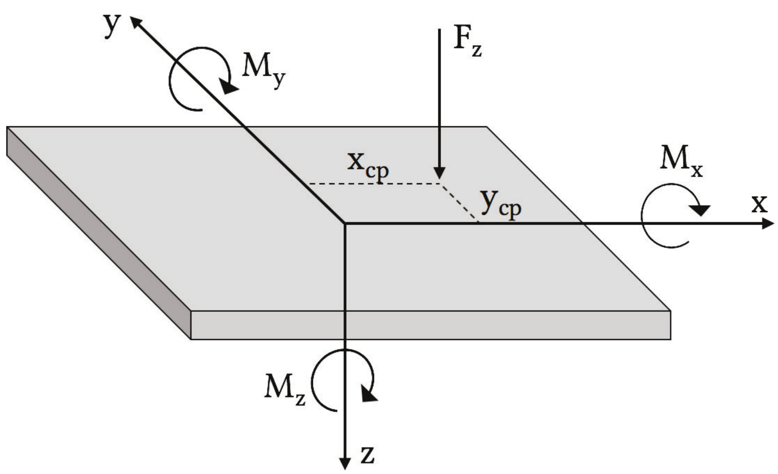

Fig. 6.2 The force plate measures three forces (F_x, F_y, F_z) and three moments (M_x, M_y, M_z). The position of the COP (Fz) can be extracted from the forces and moments.

$$V_d = \frac{\sqrt{(Xcp_i - Xcp_{i-1})^2 + (Ycp_i - Ycp_{i-1})^2}}{t_i - t_{i-1}} \tag{6.5}$$

6.2.4 Statistical analyses

The means and standard deviations were calculated for each kinematic and kinetic variable and for each excerpt and condition. A two-way ANOVA was first conducted on each parameter individually to determine the effect of the expressive conditions for each chosen musical excerpt, and whether there is an interaction effect between the two factors. A Tukey's Honest Significant Test (HSD) showed which of the expressive conditions and which excerpts differed significantly.

To investigate the effect of the conditions on the postural angles and kinetic parameters of specific regions of the score, we conducted a series of one-way ANOVAs for each section. The sections were created according to the phrasing structure and melodic repetitions. For each section, the maximum range was measured for each postural angle, as well as for the cumulative vertical force, ML and AP COP trajectories, and mean displacement velocity. A Tukey's Honest Significant Test (HSD) showed which of the expressive conditions differed significantly in each section.

We used Canonical Correlation Analysis (CCA) for the analysis of the relationships between kinematic and kinetic variables [120]. CCA measures the linear relationship between two independent variable sets, with each set including two or more variables [219]. It measures the strength of association between two canonical variates, described as the weighted average of the original variables or the projected variables. After Caramiaux and colleagues [32], we use the canonical loadings to interpret our results, which calculate the correlation between the original variables in each set and its corresponding canonical variates (i.e. the variance that the observed variables share with the canonical variates).

Finally, cross-correlation analysis was used to measure the similarities between a pair of signals as a function of time lag applied to one of them. The signals were normalized prior to applied cross-correlation. The temporal lags correspond to the highest significant correlation between both signals.

6.3 Results

The mean values of each kinematic and kinetic parameter for the 10 pianists in the different conditions and excerpts are presented in Table 6.1.

6.3.1 Comparison between musical excerpts

To evaluate whether there is an interaction effect between the musical excerpts and the conditions, a two-way ANOVA was conducted on each parameter. The two-way ANOVA

Table 6.1 Mean for all 10 pianists and standard deviation in parentheses for each kinematic and kinetic parameter. Results are shown for each condition and each excerpt.

		Kinematic parameters						**Kinetic parameters**			
	Condition	Head angle (ML) (°)	Head angle (AP) (°)	Torso angle (ML) (°)	Torso angle (AP) (°)	Hip angle (ML) (°)	Hip angle (AP) (°)	Vertical force (N)	COP displacement (ML) (mm)	COP displacement (AP) (mm)	Velocity COP displacement (mm/s)
Medtner Sonata Reminiscenza	Normal	34.3 (7.0)	33.6 (8.6)	32.7 (5.5)	27.2 (8.3)	30.8 (6.2)	13.6 (3.1)	7055.0 (3918.4)	3624.6 (958.1)	2838.3 (966.4)	112.1 (35.6)
	Deadpan	26.6 (5.5)	17.0 (3.7)	25.9 (3.5)	13.3 (1.5)	24.0 (3.9)	10.1 (1.9)	3607.0 (1267.8)	2617.7 (541.1)	2029.4 (657.5)	80.0 (25.1)
	Exaggerated	36.9 (6.4)	33.9 (8.9)	34.0 (5.1)	26.7 (7.2)	32.2 (5.6)	13.5 (3.8)	8311.4 (5331.7)	3896.2 (1019.9)	3227.2 (1092.7)	118.5 (40.0)
	Immobile	26.6 (4.6)	18.4 (5.1)	26.0 (3.5)	14.4 (3.7)	25.8 (4.5)	11.0 (3.4)	4245.7 (1824.8)	2785.6 (554.6)	2222.9 (589.8)	84.2 (22.8)
Chopin 4th Ballade	Normal	18.1 (3.4)	28.0 (7.8)	16.9 (2.2)	25.0 (7.9)	10.1 (3.0)	4.4 (1.2)	2440.0 (528.0)	2869.9 (897.7)	1549.4 (524.6)	102.3 (33.7)
	Deadpan	10.6 (3.4)	13.2 (5.8)	9.3 (2.5)	10.2 (5.0)	5.5 (2.5)	3.3 (1.8)	1843.2 (315.1)	2042.4 (493.8)	1223.9 (429.3)	74.8 (20.4)
	Exaggerated	18.6 (4.5)	28.8 (9.0)	16.8 (3.0)	24.0 (8.7)	10.5 (3.9)	5.2 (2.1)	2453.9 (508.2)	2748.8 (921.7)	1580.5 (529.1)	96.9 (36.6)
	Immobile	10.8 (2.9)	15.2 (4.3)	9.8 (2.9)	12.4 (5.1)	5.5 (2.7)	3.0 (1.4)	1905.1 (358.6)	1968.4 (584.9)	1295.1 (471.2)	73.2 (22.6)
Chopin Impromptu	Normal	19.7 (5.9)	21.9 (8.5)	16.7 (4.4)	18.5 (7.1)	8.0 (3.1)	4.1 (1.8)	1822.0 (593.2)	1639.2 (526.2)	1320.2 (583.5)	57.8 (18.9)
	Deadpan	11.2 (4.0)	9.7 (4.7)	9.4 (5.0)	8.1 (4.1)	5.3 (5.6)	2.3 (1.9)	1395.9 (363.9)	1090.3 (256.4)	1083.9 (438.1)	44.3 (11.6)
	Exaggerated	23.3 (7.4)	26.5 (10.0)	19.7 (6.8)	22.3 (10.5)	10.1 (4.0)	4.3 (1.9)	2110.5 (1023.9)	1817.9 (735.6)	1494.4(785.8)	63.2 (25.7)
	Immobile	13.3 (7.0)	12.1 (7.6)	10.1 (4.7)	9.5 (6.8)	4.6 (3.0)	2.3 (1.1)	1410.4 (474.1)	1101.6 (290.0)	1079.0 (478.9)	44.0 (13.9)

reveals a significant interaction effect between the excerpts and the conditions for the cumulative force only.

Kinematic parameters

A significant main effect of the excerpts was observed for each kinematic parameter. More specifically, there is a significant difference between the Sonata and the Ballade (p $<$ .001), and between the Sonata and the Impromptu ($p < .001$) for all postural angles, but not between the Ballade and the Impromptu. Variations in postural angles for the head [$F(2, 119) = 111.3$, $p < .001$], torso [$F(2, 119) = 185.3$, $p < .001$] and hip [$F(2, 119) = 331.1$, $p < .001$] are larger in the ML direction between the Sonata and the Ballade than in the AP direction.

Kinetic parameters

The mean cumulative force used by pianists for the excerpts and the expressive conditions is shown in Figure 6.3. The two-way ANOVA revealed a significant interaction effect between the conditions and the excerpts [$F(6, 119) = 6.6$, $p = .01$]. This interaction comes from the fact that both the Sonata and the Ballade present a significant main effect of the conditions, whereas the Impromptu does not. As shown in Table 6.1, the standard deviation between pianists is larger for the performances of the Sonata, for which a significant difference is observed only between the deadpan and exaggerated conditions. For the Ballade, the normal condition differs significantly with the deadpan, exaggerated and immobile conditions. As an example, Figure 6.4 shows one pianists' force data while performing the Ballade in the four performance conditions. The ML COP displacement discriminates all the excerpts significantly [$F(2, 119) = 69.0$, $p < .001$]. The velocity of the COP displacement also differs in a significant way between the Sonata and the Impromptu and between the Ballade and the Impromptu [$F(2, 119) = 31.8$, $p < .001$], but not between the Sonata and the Ballade.

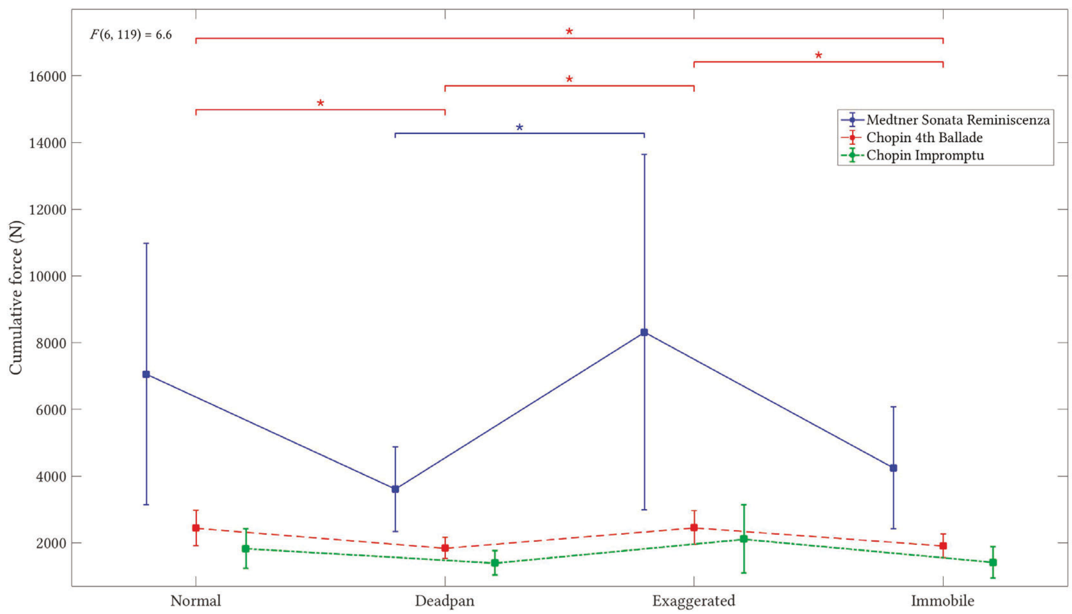

Fig. 6.3 Average cumulative force for each of the excerpts and expressive conditions. The squares represent the mean and the vertical bars the standard deviation between pianists. The stars and horizontal bars represent the Tukey's HSD pair-wise comparisons between the conditions (* = $p < .05$). An interaction effect was observed between the excerpts and conditions.

6.3.2 Comparison between performance conditions within each excerpt

To determine the regions where pianists differ between the expressive conditions, a one-way ANOVA was conducted within each section for each excerpt. For the Sonata, we considered melodic repetitions, whereas for the Ballade and the Impromptu we used phrase boundaries. No significant difference was found between the normal and exaggerated conditions for any of the parameters and excerpts.

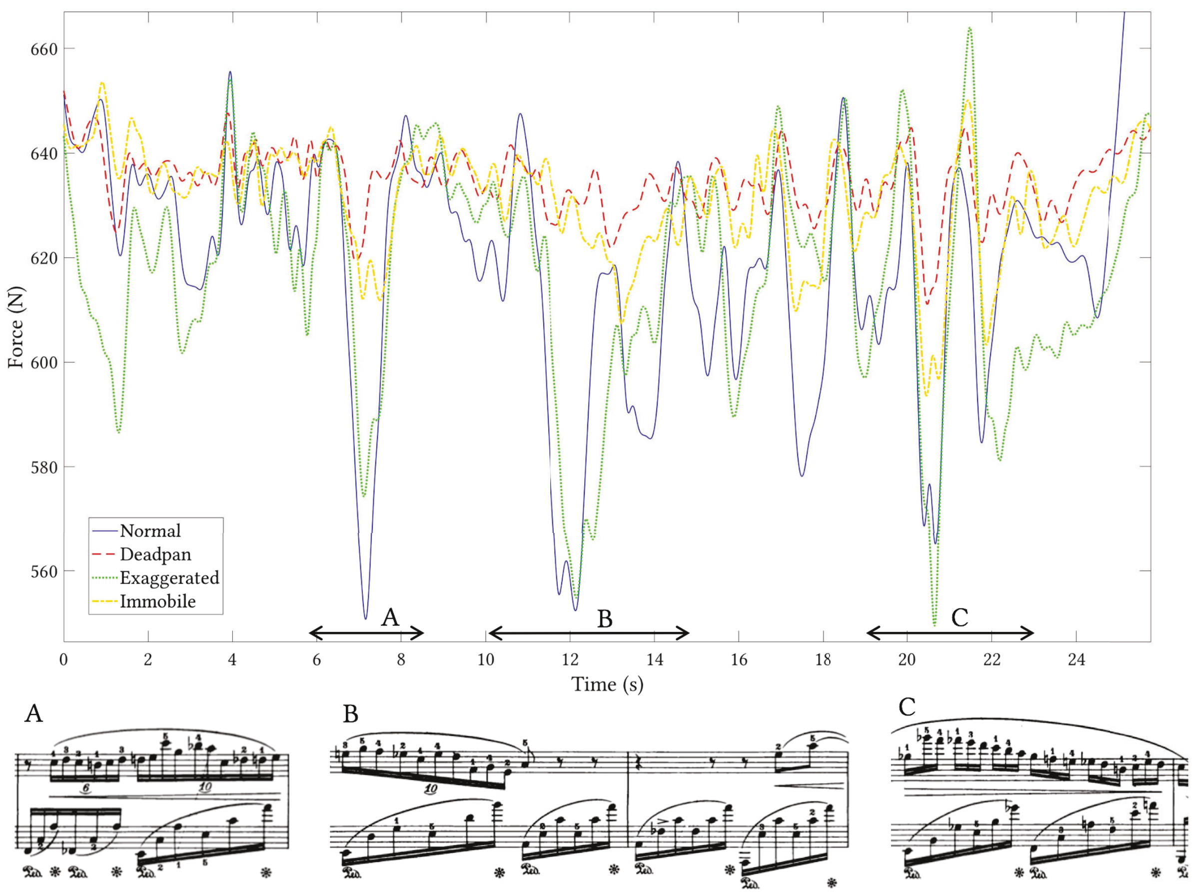

Fig. 6.4 Pianist 4's force data for the Chopin 4th Ballade in the four performance conditions. The arrows represent the regions with large variations between the normal condition and the deadpan and immobile conditions. No significant differences were observed between the normal and exaggerated conditions.

Medtner Sonata Reminiscenza A Tukey's Honest Significant Test shows that the head and torso angles in the AP direction are significantly different between the normal, deadpan and immobile conditions for all the sections, but not in the ML direction (Table 6.2). The torso and hip angles in the ML direction only differ during the three first sections and the last two, which respectively coincide with crescendo ascending motifs and large ascending arpeggios that span five octaves. Pianists' COP displacements also differ significantly at the end of the excerpt. Figure 6.5 shows 1 pianist's stabilogram of the ML and AP COP displacements for the Sonata. The difference between conditions can be observed mainly in the ML direction and is greater in the exaggerated condition. The vertical force and the COP velocity do not show significant differences between the normal and other conditions.

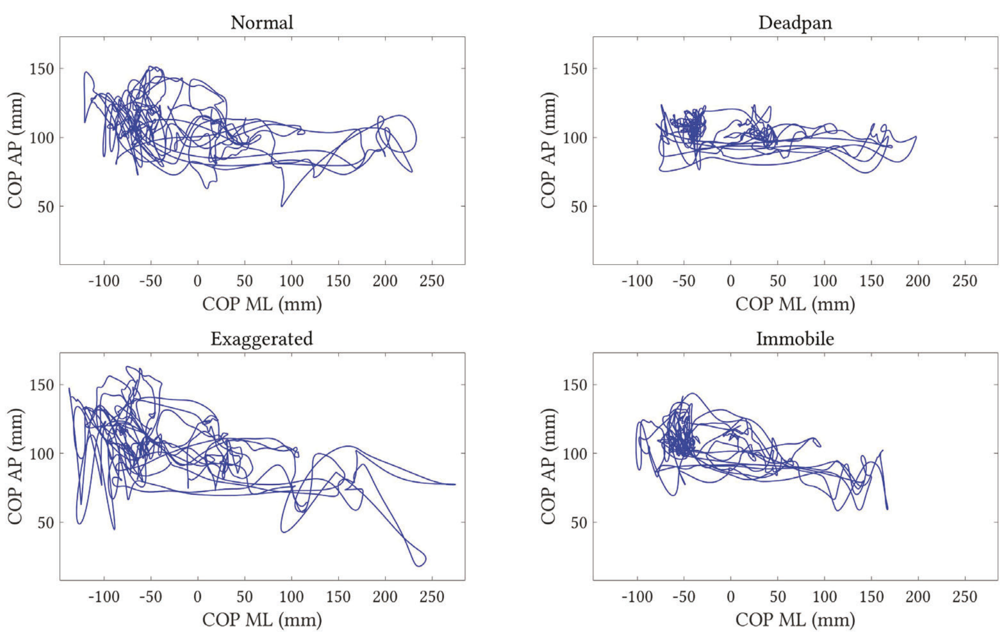

Fig. 6.5 Stabilogram of pianist 4's performance of the Medtner Sonata Reminiscenza showing the ML and AP displacements of the COP (postural sway) for the different expressive conditions.

Chopin 4th Ballade Table 6.3 demonstrates that pianists use angles from the upper body with significant amplitude difference between the conditions. Contrarily to the Sonata, the normal condition varies significantly from the deadpan and immobile conditions in all sections for the head, torso and hip angles in the ML direction, and only at sections 2 and 5 for the head and torso angles in the AP direction. Sections 2 and 5 both have large intervals to reach in the melody usually chromatic. The vertical force differs between the conditions at sections 3, 4 and 5, which coincides with the repetition and modulation of the theme with a louder sound dynamic. Conversely to the Sonata and the Impromptu, the ML COP displacements are larger for four pianists during the normal performance for the Ballade, even more than for the exaggerated performance (Figure 6.6).

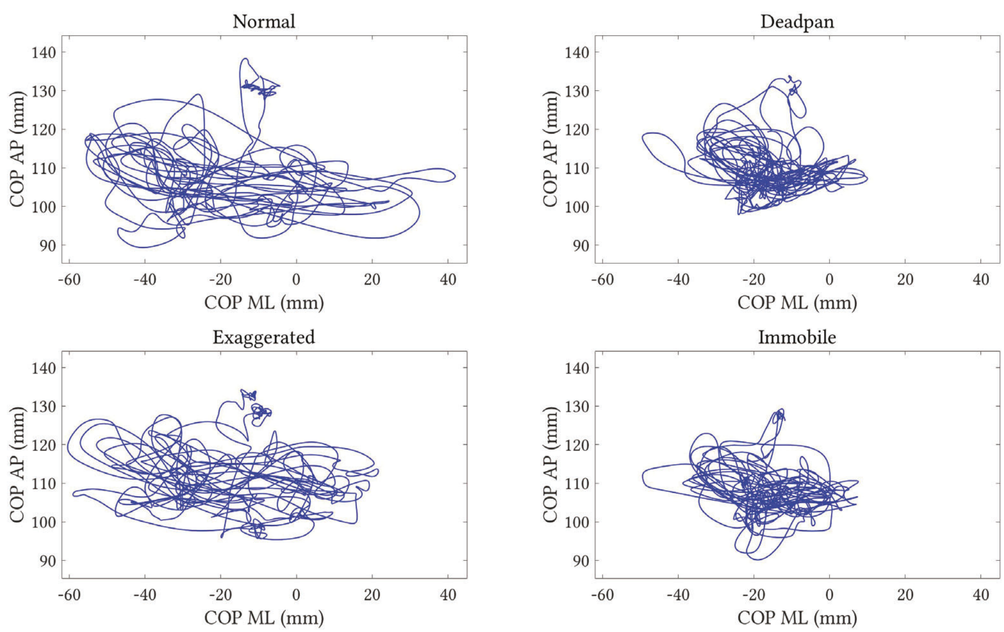

Fig. 6.6 Stabilogram of pianist 1's performance of the Chopin 4th Ballade showing the ML and AP displacements of the COP (postural sway) for the different expressive conditions.

Chopin Impromptu Table 6.4 shows that all postural angles vary significantly between the conditions for the whole excerpt. However, no kinetic parameters vary significantly between the normal performance and other conditions.

6.3.3 Relationship between kinematic and kinetic data

CCA was used to analyze the relationships between the kinematic and kinetic features and to identify key factors in each set of variables. Since we are interested in the effect of movement on the relationships between kinematic and kinetic parameters, we chose to examine specifically the normal and immobile performances for each excerpt to understand better the impact of QoM on posture.

Medtner Sonata Reminiscenza Figures 6.7 and 6.8 show the canonical loadings for the first and second components for the normal and immobile conditions of the Sonata. For both conditions, the head (loadings: 0.93), torso (loadings: 0.98) and hip (loadings: 0.99) angles in the ML direction are the most represented in the first canonical component and are strongly correlated to the ML COP displacement. Head and torso angles in the AP direction contribute the most to the second canonical function in the kinematic space and are strongly associated to the vertical force. Displacement velocity did not contribute much to the first (normal loadings: 0.12; immobile loadings: 0.26) or second functions (normal loadings: 0.23; immobile loadings: 0.20). Interestingly, the second function's canonical loadings show that the relationship between the head and torso angles and the force is less well defined during the immobile condition than for the normal performance, with largest differences between pianists' loadings for the immobile condition.

Table 6.2 Results from the one-way ANOVA performed on each kinematic and kinetic parameter for the Medtner Sonata Reminiscenza. Pair-wise comparisons (Tukey-Kramer) significant at $p < .05$ were conducted to identify which conditions differ with the normal performance and are marked by an exponent. ^{a} = significant difference between normal and deadpan; ^{b} = significant difference between normal and immobile.

		Medtner Sonata Reminiscenza							
		Section 1 Bars 1-4	**Section 2** Bars 5-10	**Section 3** Bars 11-12	**Section 4** Bars 13	**Section 5** Bars 14-17	**Section 6** Bars 18-19	**Section 7** Bars 20-21	**Section 8** Bars 21-22
Head angle	F (3, 39)	4.2	2.4	3.6	8.3	3.0	2.5	58.3	27.5
(x-axis)	p	**.01**	.08	**.02**	< **.001**^{a,b}	**.04**	.07	< **.001**^{a,b}	< **.001**^{a,b}
Head angle	F (3, 39)	12.7	8.4a	13.2	11.8	7.3	10.1	4.7	11.3
(y-axis)	p	< **.001**^{a,b}	< **.001**^{a}	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a}	< **.001**^{a,b}	**.007**^{a}	< **.001**^{a,b}
Torso angle	F (3, 39)	8.8	6.7	2.5	2.2	2.5	5.1	8.1	9.6
(x-axis)	p	< **.001**	**.001**^{a}	.07	.11	.08	**.005**	< **.001**^{a,b}	< **.001**^{a,b}
Torso angle	F (3, 39)	11.4	10.9	11.2	12.3	9.4	9.6	5.9	8.1
(y-axis)	p	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	**.002**^{a,b}	< **.001**^{a,b}
Hip angle	F (3, 39)	7.6	9.6	9.9	1.5	2.4	5.1	6.3	5.5
(x-axis)	p	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	.23	.09	**.005**	**.001**^{a}	**.003**^{a}
Hip angle	F (3, 39)	7.3	79.5	83.5	0.5	1.1	4.3	1.1	1.8
(y-axis)	p	< **.001**^{a}	< **.001**^{a,b}	< **.001**^{a,b}	0.66	0.35	**.01**	.37	.16
Vertical force	F (3, 39)	1.1	2.5	3.7	4.5	3.3	3.8	2.8	1.7
	p	.36	.07	**.02**	**.009**	**.03**	**.01**	.06	.17
CoP displacement	F (3, 39)	4.9	4.0	4.6	3.6	2.2	2.8	5.4	3.9
(x-axis)	p	**.006**	**.01**	**.008**	**.02**	.11	.06	**.003**^{a}	**.02**
CoP displacement	F (3, 39)	1.1	1.4	3.8	5.3	1.5	2.1	7.3	6.1
(y-axis)	p	.36	.27	**.02**	**.004**	.23	.11	< **.001**^{a}	**.002**^{a}
Displacement	F (3, 39)	2.8	2.9	5.0	2.7	1.8	2.4	4.3	0.6
velocity	p	.06	**.05**	**.005**	.06	.16	.09	**.01**	.64

Table 6.3 Results from the one-way ANOVA performed on each kinematic and kinetic parameter for the Chopin 4th Ballade. Pair-wise comparisons (Tukey-Kramer) significant at $p < .05$ were conducted to identify which conditions differ and are marked by an exponent. ^{a} = significant difference between normal and deadpan; ^{b} = significant difference between normal and immobile.

		Chopin 4th Ballade				
		Section 1 Bars 1-2	**Section 2** Bars 3-4	**Section 3** Bars 4-5	**Section 4** Bars 5-7	**Section 5** Bars 7-8
Head angle (x-axis)	F (3, 39)	7.4	10.3	7.1	6.4	7.0
	p	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	**.001**^{a}	< **.001**^{a}
Head angle (y-axis)	F (3, 39)	3.2	11.4	5.4	3.9	15.8
	p	**.03**	< **.001**^{a,b}	**.004**	**.02**	< **.001**^{a,b}
Torso angle (x-axis)	F (3, 39)	6.6	9.8	13.7	13.2	12.2
	p	**.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}	< **.001**^{a,b}
Torso angle (y-axis)	F (3, 39)	4.3	12.0	4.5	3.4	13.8
	p	**.01**	< **.001**^{a,b}	**.009**	**.03**	< **.001**^{a,b}
Hip angle (x-axis)	F (3, 39)	4.9	7.4	5.5	7.5	6.8
	p	**.006**^{b}	< **.001**^{b}	**.003**^{b}	< **.001**^{a,b}	< **.001**^{a,b}
Hip angle (y-axis)	F (3, 39)	9.6	7.2	2.5	9.1	3.3
	p	< **.001**	< **.001**	.07	< **.001**^{a,b}	**.03**
Vertical force	F (3, 39)	4.5	1.0	5.5	5.9	4.8
	p	**.008**	.41	**.003**^{a}	**.002**^{a}	**.007**^{a}
CoP displacement (x-axis)	F (3, 39)	2.5	1.2	3.7	3.5	3.7
	p	.08	.32	**.02**	**.03**	**.02**
CoP displacement (y-axis)	F (3, 39)	0.5	0.8	2.6	1.3	1.6
	p	.66	.52	.06	.29	.21
Displacement velocity	F (3, 39)	1.6	1.4	2.9	1.8	1.4
	p	.21	.27	**.05**	.17	.27

Table 6.4 Results from the one-way ANOVA performed on each kinematic and kinetic parameter for the Chopin Impromptu. Pair-wise comparisons (Tukey-Kramer) significant at $p < .05$ were conducted to identify which conditions differ and are marked by an exponent. ^{a} = significant difference between normal and deadpan; ^{b} = significant difference between normal and immobile.

		Chopin Impromptu				
		Section 1 Bars 1-2	**Section 2** Bars 2-4	**Section 3** Bars 4-6	**Section 4** Bars 7-8	**Section 5** Bars 9-10
Head angle (x-axis)	F (3, 39)	26.1	22.3	6.9	11.1	4.8
	p	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a}	$<$ **.001**^{a,b}	**.006**
Head angle (y-axis)	F (3, 39)	17.1	16.1	7.8	8.5	9.0
	p	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}
Torso angle (x-axis)	F (3, 39)	28.4	13.8	7.7	17.5	8.4
	p	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}
Torso angle (y-axis)	F (3, 39)	14.7	11.8	7.2	7.0	8.3
	p	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a}	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}
Hip angle (x-axis)	F (3, 39)	14.5	11.9	8.4	15.4	7.1
	p	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}	$<$ **.001**^{a}	$<$ **.001**^{a,b}	$<$ **.001**^{a}
Hip angle (y-axis)	F (3, 39)	**10.0**	**10.6**	**6.8**	**68.5**	**8.2**
	p	$<$ **.001**^{a,b}	$<$ **.001**^{a}	$<$ **.001**	$<$ **.001**^{a,b}	$<$ **.001**^{a,b}
Vertical force	F (3, 39)	2.9	1.9	2.0	1.3	3.2
	p	**.05**	.15	.14	.29	**.03**
CoP displacement (x-axis)	F (3, 39)	3.6	5.2	3.4	2.8	3.9
	p	**.02**	**.004**	**.03**	.06	**.02**
CoP displacement (y-axis)	F (3, 39)	1.9	0.9	1.2	0.9	0.9
	p	.15	.45	.32	.46	.46
Displacement velocity	F (3, 39)	3.3	1.8	1.8	1.1	2.4
	p	**.03**	.16	.16	.37	.08

Chopin 4th Ballade The head angle in the ML direction only makes a marginal contribution to the first function (normal loadings: 0.76; immobile loadings: 0.58). Figures 6.9 and 6.10 show that, for the first canonical function, there is less agreement between pianists' loadings for the head and torso angles during the performances of the Ballade than those of the Sonata. Moreover, both hip angles are correlated to the ML COP displacement. The second canonical function does not exhibit a correlation between kinetic and kinematic parameters as high as for the Sonata. The force contributes to the second function with a median of respectively 0.90 and 0.88 for the normal and immobile conditions. Overall, no major difference is observed between the normal and immobile conditions for the second function.

Chopin Impromptu The first function's canonical loadings of the hip (normal loadings: 0.97; immobile loadings: 0.95) and torso (normal loadings: 0.92; immobile loadings: 0.87) angles in the ML direction are closely associated to the ML COP displacement (loadings: 0.98 for both conditions), whereas the head presents a freer behavior. Figures 6.11 and 6.12 show that the strength of the relationship between both sets of parameters is similar for both conditions. The second component's canonical loadings reveal a correlation between the vertical force and the head and torso angles.

Cross-correlation analysis

Finally, to understand why the COP in the ML direction is also associated to the hip angle in the AP direction, more specifically for the Ballade, we calculated the cross-correlation between both signals. Cross-correlation measures the similarity between a pair of signals as a function of time lag applied to one of them, where temporal lags correspond to the highest significant correlation between both signals.

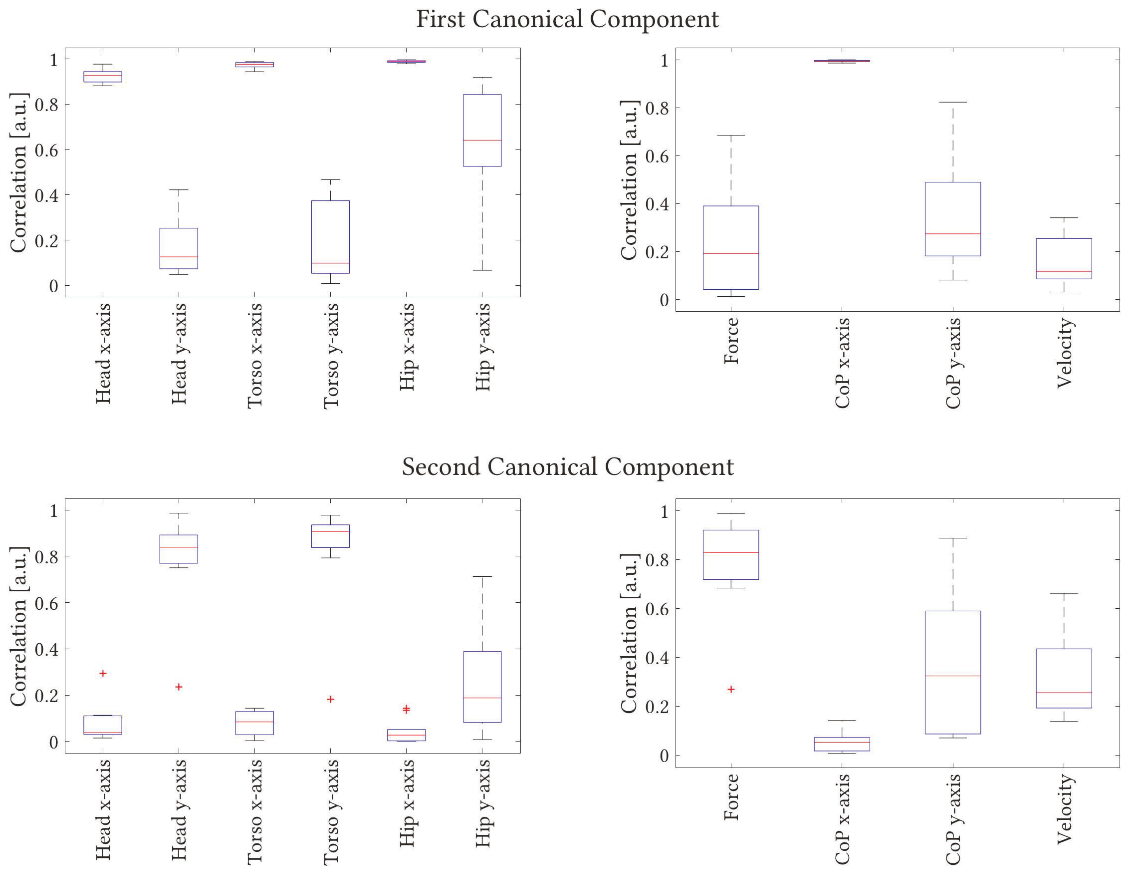

Fig. 6.7 Medtner Sonata Reminiscenza - normal condition. The medians (in red) for all pianists' kinematic parameter loadings are plotted on the left side and those for the kinetic parameter loadings on the right side of the graph. Each row represents one canonical component or function.

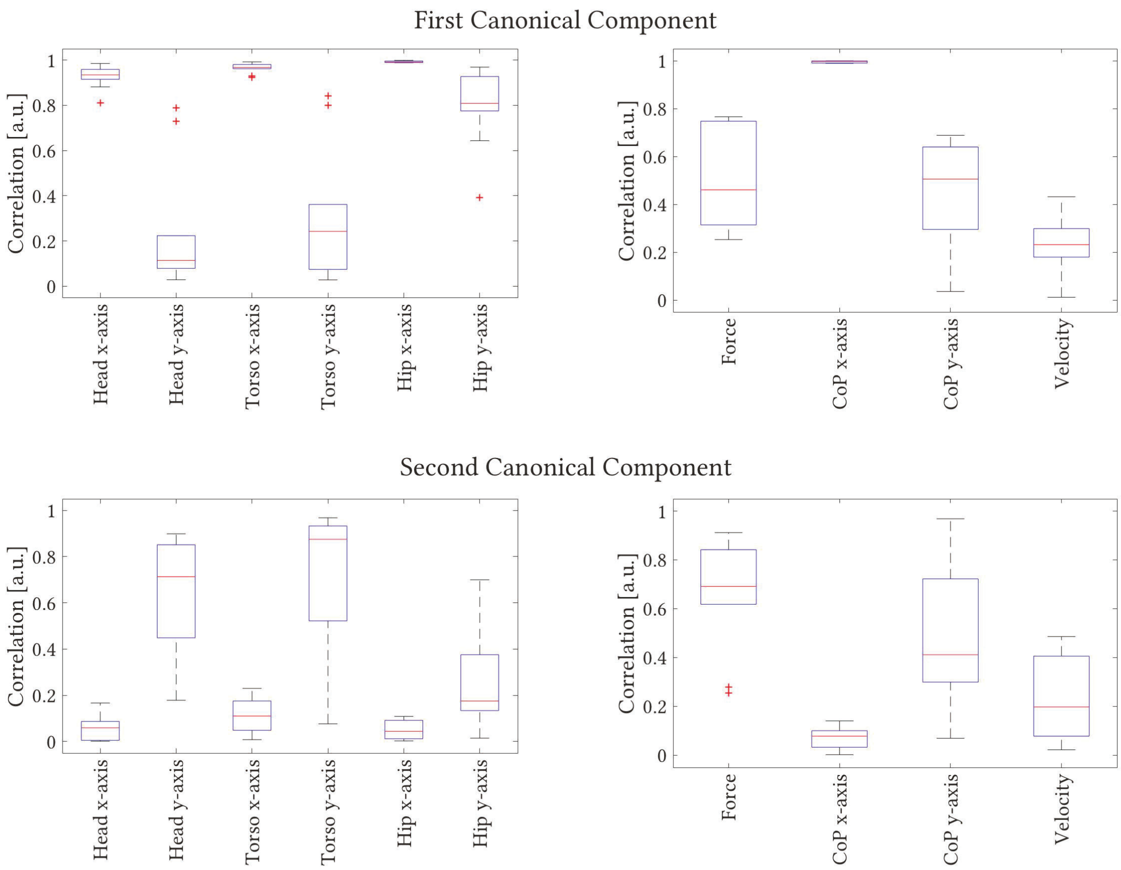

Fig. 6.8 Medtner Sonata Reminiscenza - immobile condition. The medians (in red) for all pianists' kinematic parameter loadings are plotted on the left side and those for the kinetic parameter loadings on the right side of the graph. Each row represents one canonical component or function.

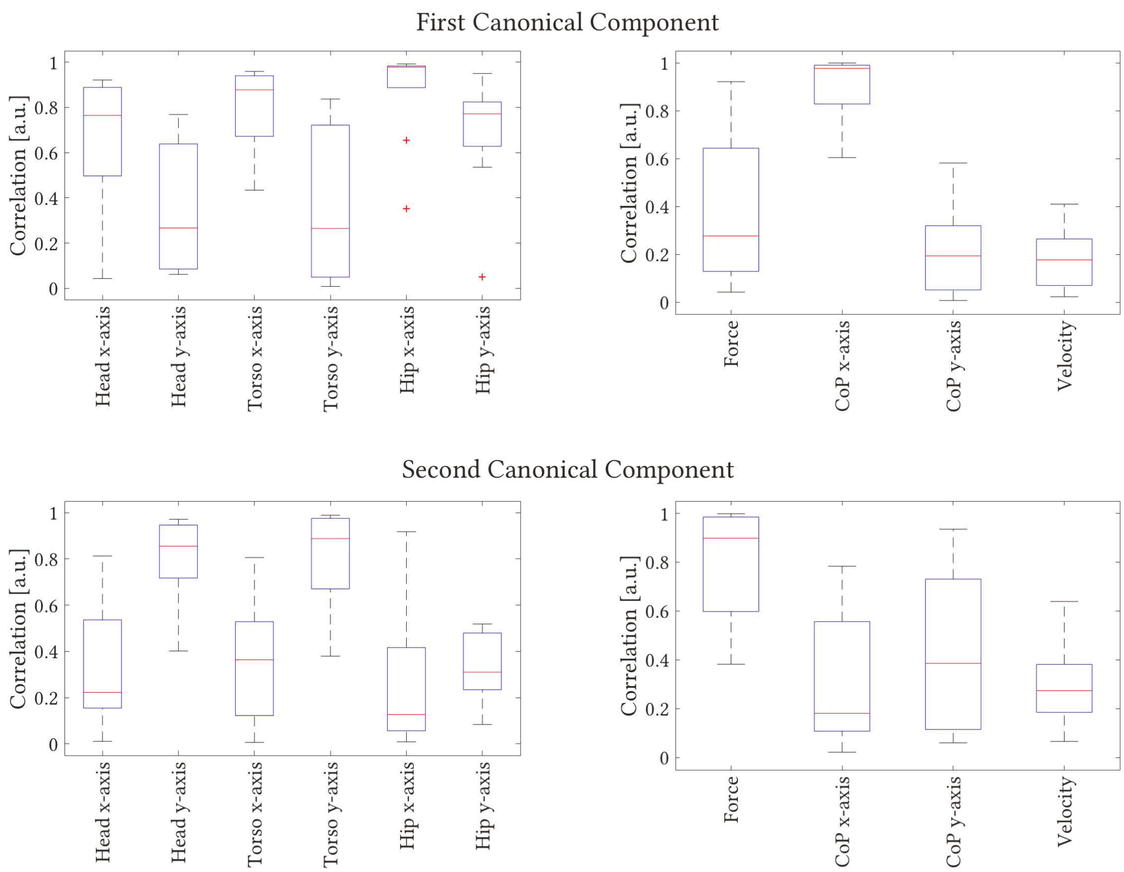

Fig. 6.9 Chopin 4th Ballade - normal condition. The medians (in red) for all pianists' kinematic parameter loadings are plotted on the left side and those for the kinetic parameter loadings on the right side of the graph. Each row represents one canonical component or function.

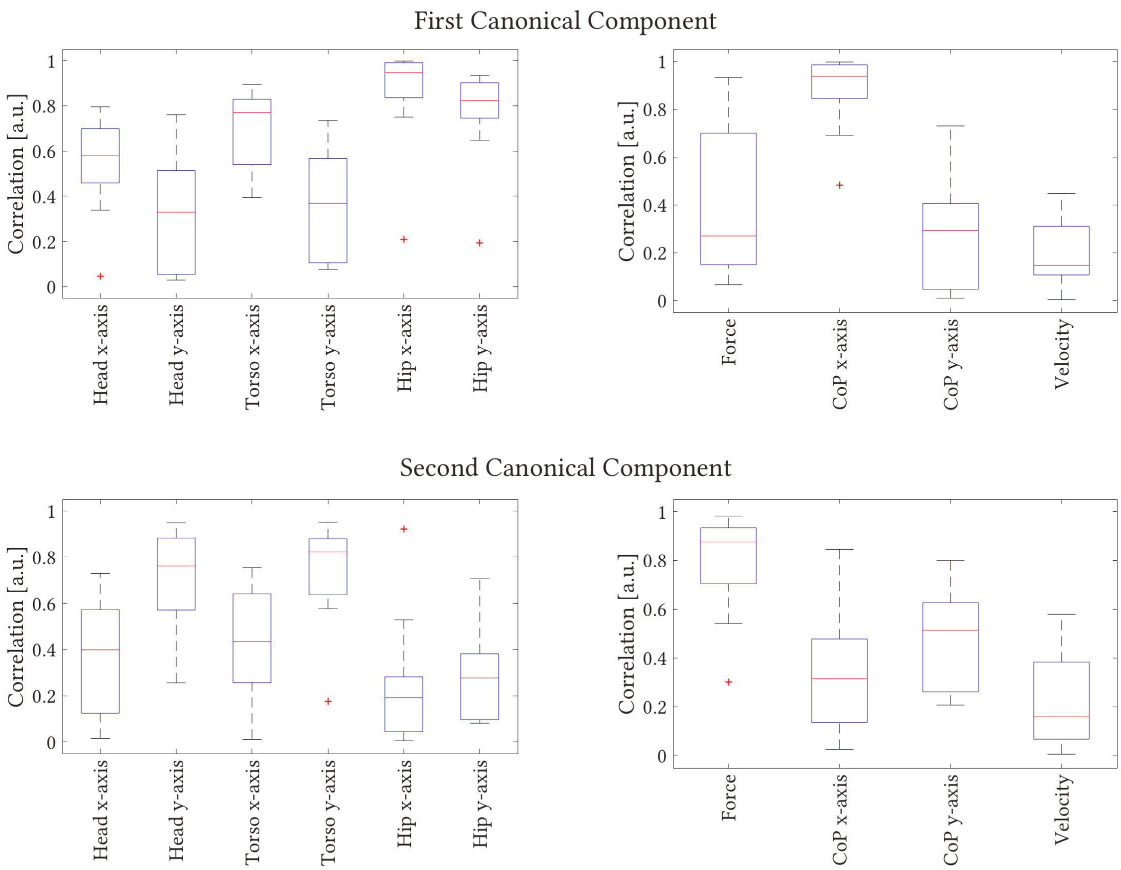

Fig. 6.10 Chopin 4th Ballade - immobile condition. All pianists' kinematic parameter loadings are plotted on the left side and kinetic parameter loadings on the right side of the graph. Each row represents one canonical component or function.

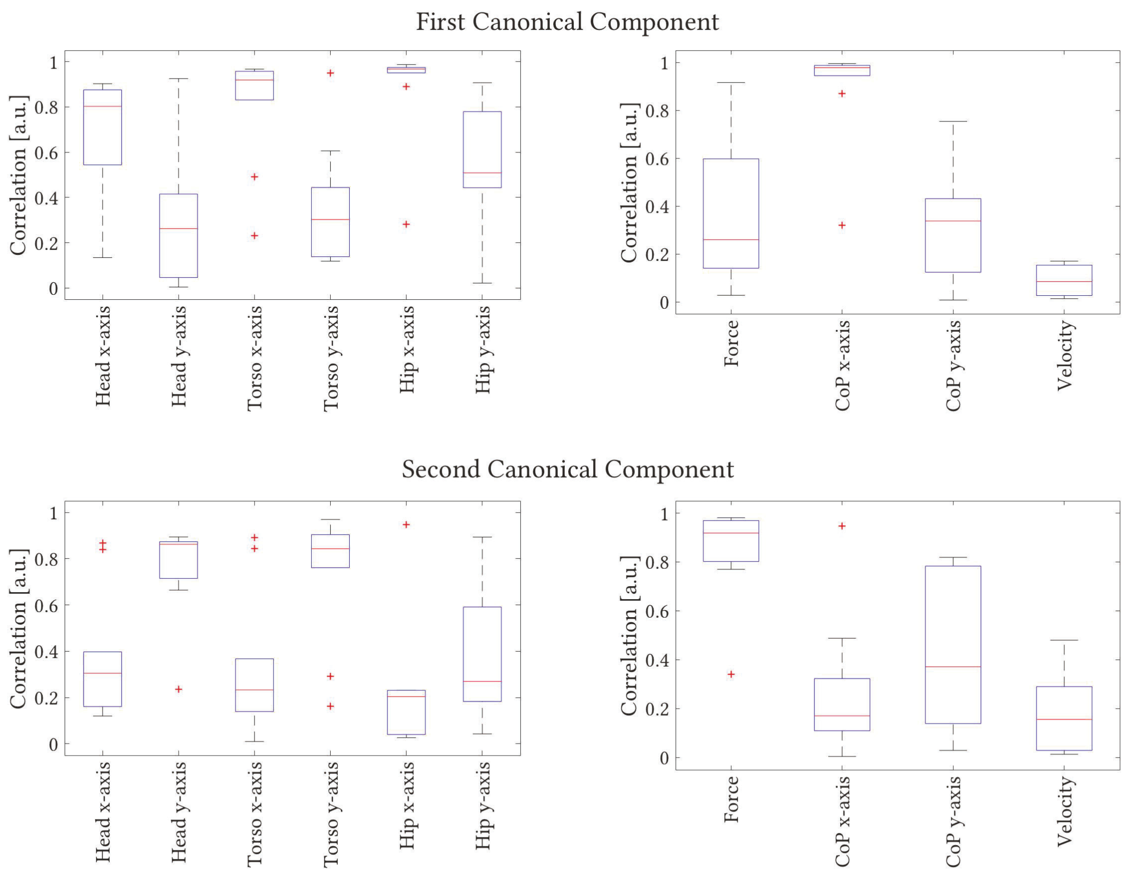

Fig. 6.11 Chopin Impromptu - normal condition. The medians (in red) for all pianists' kinematic parameter loadings are plotted on the left side and those for the kinetic parameter loadings on the right side of the graph. Each row represents one canonical component or function.

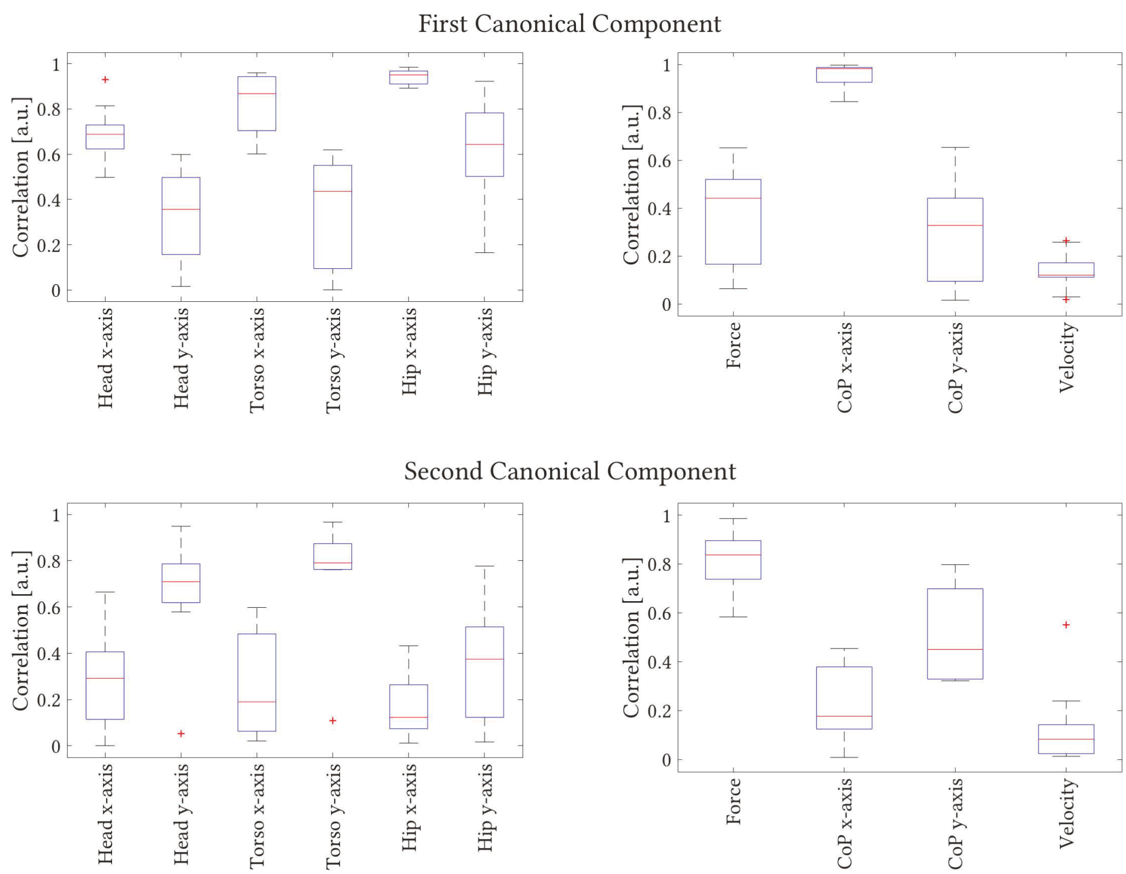

Fig. 6.12 Chopin Impromptu - immobile condition. The medians (in red) for all pianists' kinematic parameter loadings are plotted on the left side and those for the kinetic parameter loadings on the right side of the graph. Each row represents one canonical component or function.

On average, temporal lags are smaller for both conditions of the Ballade, with time lags of 0.03s and 0.04s for the normal and immobile conditions, as compared to the two other excerpts, and larger for the Impromptu. Time lags of 0.08s and 0.13s can be observed for the normal and immobile conditions of the Sonata and 0.28s and 0.22s for the Impromptu.

6.4 Discussion

This research investigated expert pianists' postural sway when playing different Romantic excerpts in various performance conditions. We also discussed the relationships between the upper body kinematics and kinetics in normal and immobile conditions.

Pianists' COP displacements One important finding of this study was that pianists' COP displacements were not larger in an immobile manner as compared to a normal condition. Since large deviations in magnitude of the COP displacements were associated to a greater postural instability [205], our results suggest that playing as naturally as possible while restraining the body movements does not affect pianists' postural stability and control. However, Rozé [210] studied cellists' posture in a condition where the movements of the head and torso were physically blocked and found that it occasioned a greater instability in the COP deviation. These results are in accordance with biomechanical studies that have shown that a sitting posture where the back rests increases the ML COP displacements [171] and the levels of back muscle activation [107]. A passive stiffening of the torso and hip also increases the risk of loss of balance during standing in both the ML and AP directions [110]. Therefore, in our case, a forced immobilization of upper body movements, as opposed to consciously immobilizing the movements only, could have produced different results and disrupted pianists' postural stability.

On average, pianists' COP displacements were larger in an exaggerated performance as compared to all the other conditions, for the Sonata and the Impromptu, but not for the Ballade. Previous studies have shown that pianists use larger QoM when performing in an exaggerated manner in specific areas of the score [220, 232]. While restraining the movements mentally does not affect pianists' COP displacements, we found that performing with an overly exaggerated expression could be detrimental to postural stability.

For all the excerpts, ML COP displacements differed significantly between the conditions in more regions than the COP displacements in the AP direction. These results are similar to Cholewicki and colleagues' findings [35], showing that during unstable sitting, the COP displacement is larger in the ML direction than in the AP direction when the feet are supported to create a 90°angle with the knee. This indicates that pianists' postural instability may be caused by the movements along the keyboard and accentuated by the level of expression and movements. It also suggests that pianists' upper body muscles work more at stabilizing the center of mass during displacements in the ML direction, since postural control can be more easily achieved by using the support and force of the legs in the AP direction.

Comparisons between the musical excerpts We found that only the ML COP displacement, the vertical force, and the COP displacement velocity could characterize each excerpt and discriminate the Ballade from the Impromptu. Moreover, although the Ballade and the Impromptu differed greatly in terms of rhythmic structure and melodic and harmonic complexity, postural angle ranges were comparable for both excerpts. These findings suggest that the structural features characterizing a piece can have a strong influence on pianists' use of kinematic parameters, whereas the range of amplitude of body angles is not always dependent on the technical complexity of an excerpt and its musical structure.

Comparisons between the performance conditions Post Hoc tests revealed that for the Sonata, pianists' body angles measured in the AP direction varied more between the expressive conditions than in the ML direction, and more specifically between the normal and deadpan conditions. For the Ballade, pianists performed the conditions with significantly different amplitudes of postural angles mainly in the ML direction. Finally, for the Impromptu, body angles measured in both directions were found statistically different between the conditions. One explanation could be that the Sonata requires large lateral movements which may prevent pianists to exaggerate or reduce them when playing the different conditions.

Previous studies have demonstrated that the head velocity and QoM showed meaningful differences between different performance conditions [26, 62], and between emotions [33, 54]. In this study, even body parts with less degrees of freedom such as the hip varied significantly between the conditions in terms of amplitude of angles, and more specifically for the Impromptu. It is interesting to note that for pieces with simpler melodies such as the Impromptu, pianists' hip amplitude of motion is more connected with the level of expression than for more technical excerpts.

No significant differences between the normal and other expressive conditions were found for any of the kinetic variables during the performances of the Impromptu. This suggests that pianists use different postural angles from the upper body to communicate different expressive intentions, whereas kinetic parameters are less affected when performing an excerpt with simple and delicate melody, and which does not entail large sound variations such as the Impromptu. Two-way ANOVA showed significant changes in force between the normal performance and other conditions occurred only for the Ballade, during the transition leading to the modulated theme. This means that the use of force depends on the level of expression and movement when specific structural conditions are met.

Canonical correlation analysis We showed that CCA is useful to investigate how pianists use body angles in conjunction with kinetic variables, as well as which parameters are more influenced by the type of music performed and the quantity of movements. The first function demonstrated how closely the postural angles related to the spinal movements, such as head, torso and hip angles along the ML direction, work together and how they are connected to the COP displacements for pieces that require more dynamic and fast movements along the keyboard such as the Sonata. However, the head angle presented a more independent behavior for the Ballade and the Impromptu and had no clear correlation with specific kinetic parameters as is the case for the Sonata. The results from the second function revealed that the upper body angles used along the y-axis tend to have a strong correlation with vertical force no matter the excerpts, although that relationship was more visible for the Sonata and the Impromptu.

Previous studies have shown that when a pressed touch is used at fast tempi and for louder tones, pianists do not benefit from gravity, but instead use a forward motion toward the keyboard, which reduces muscular effort during repetitive energetic keystrokes [80–82]. Our findings showed that pianists' forward motion is often accompanied by a drop in vertical force applied on the stool as they use the support of their legs to direct the weight towards the floor. Contrarily to what we hypothesized, we found that the immobile condition had little incidence on the correlation between the vertical force and the postural angles in the AP direction, principally for the Ballade and the Impromptu. CCA also revealed that there was a strong correlation between pianists' ML COP displacement and the hip angle in the AP direction for the Ballade, which may seem counterintuitive. The periodic nature of the Ballade excerpt, caused by the rhythmic structure and the motivic melodic line, occasioned a strong connection between the hip angles in both directions. Cross-correlation analysis showed that for most pianists, the changes in amplitude in upper body angles were periodic, as found MacRitchie and Bailey [157] and Shoda and Adachi [220] when pianists perform excerpts with a constant rhythm.

6.5 Conclusion

In summary, this research provided insight with regard to pianists' postural control strategies to communicate different expressions when playing various Romantic excerpts, and also when they consciously immobilize their movements while trying to produce a natural sound expression. The results revealed how one particular type of writing and expressive intention can affect pianists' postural sway. Although the Ballade is very different from the Impromptu in terms of level of technical complexity, defined here as few passages of rest, high speed of execution, and high difficulty in terms of the rhythm and melodic form, similar range of amplitudes of postural angles were used. Moreover, for both excerpts, no significant differences between the conditions were found for the kinetic parameters, except for the vertical force for the Ballade. The performances of the Sonata were distinct from the other two excerpts in terms of COP displacements probably because of the strong connection observed between the head, torso and hip angles and the COP displacements in the ML direction.

Since this research investigated the common patterns in a group of experimented pianists, further studies should also focus on the individual strategies that pianists employ to understand better idiosyncratic movements and the link with structural characteristics. It was previously shown that anthropometric data, such as weight, height, segment length, can influence the degree of variation in COP displacements [35], and therefore may affect pianists' postural control differently when playing with various levels of expression or when suppressing certain movements from the performance. Additional research is needed to investigate the impact of various levels of expression on pianists' muscle tension and ligament forces by incorporating anthropometric data to the results on movements kinematics and kinetics.

Somatic methods, such as the Alexander technique, the Feldenkrais method, or the Body Mapping approach, aim to aid musicians in injury prevention and rehabilitation or improving kinesthetic awareness [225]. Unfortunately, pedagogical approaches rarely integrate advice related to the posture of the whole body in relation to the musical structure and expression. The current study highlighted how experienced pianists adapt their posture according to different pieces and expressive intentions. These findings, incorporated to current pedagogical methods, could help teachers improve their feedback with more systematic and adapted strategies based on scientific results on musical expression, body movements and posture. Eventually, to understand better how kinetic and kinematic variables vary in function of anthropometric data of individual pianists could provide teachers with tools to personalize their lessons according to the physical characteristics of different pianists.

Chapter 7

Discussion

The articles presented in this thesis have helped to further demonstrate that, in piano performance, the movements from the whole body may have an impact on how the communication of structural and expressive parameters is perceived. They each have specific functions (e.g. expressive, postural, perceptual) that strongly depend on the musical context. The main research questions of this thesis were:

1. Does the choice of musical excerpts influence pianists' use of QoM, force and audience perception?

2. How do experienced pianists use QoM and expressive timing in relation to structural parameters of pieces with varied technical difficulties and in different performance conditions?

3. Are musically trained auditors able to discriminate between different performance conditions when provided with one perceptual mode at a time (visual or auditory) or both?

4. Does a performance where pianists are asked to restrain body movements while trying to emulate a natural performance affect the sound parameters?

5. How do experienced pianists adjust their posture and the kinetic aspects of their performance when playing different musical excerpts in various performance conditions?

7.1 Choice of excerpts

In order to answer these questions in a way that is based upon existing research on the relationships between musical structure and pianists' body movements (e.g. [60, 61, 220, 232]), we specifically chose three pieces from the Romantic repertoire, namely the Sonata Reminiscenza, the Chopin 4th Ballade and the Chopin Impromptu.

The following works illustrate the disparity of the results when choosing pieces that differ in terms of the level of technical difficulty and stylistic features. Research has already acknowledged the relationship between the swaying motion of performers and the musical structure. It was proposed that when pianists performed different phrases from Chopin's preludes that have similar rhythmical patterns, they also use similar motion profiles [156, 157], revealing that different pianists shape their movements according to the phrasing structure and rhythm of the piece. However, while pianists' swaying movement are synchronized with the rhythmical patterns in simple piano pieces, this may not happen for more complex excerpts [28]. Indeed, pianist's head movements did not synchronize with the two-bar phrasing structure of a Scriabin Etude.

Stylistic and technical features of musical pieces can have a strong impact on the synchronization of the movements with structural parameters, on pianists' ability to modulate the level of expression and movements, and also on the occurrence of recurrent motion patterns between performers. Moreover, most of these studies were based on the interpretation of data from an arbitrarily chosen single piece or excerpt, which did not allow comparisons between the performers' styles and different pieces. In this research, we have shown that different excerpts presenting various levels of complexity do influence pianists' expressive and physical reactions to the music. The next sections summarize the outcomes of the present work and their relationships with the findings from the literature.

7.2 Relationships between the musical structure, tempo and QoM

Chapter 4 examined the variations in duration between the conditions for each performance. Interestingly, even though pianists performed the excerpts and the conditions at various tempi, the duration of pianists' performances was overall less affected by the QoM used than by the level of expression regardless of the technical difficulty of the excerpt, as Thompson and Luck [232] found for the Chopin Prelude. Contrarily to what Wanderley and colleagues [252] found for clarinetists, on average, pianists did not necessarily perform the immobile condition faster than the normal one. Clarinetists' sense of timing was affected when playing a complex clarinet piece from Stravinsky [252]in an immobilized manner, whereas pianists' timing during Chopin Prelude immobile performance was similar to a standard performance [232]. A possible explanation could be that the deadpan condition was not used in their study, and thus, the immobile condition – defined as a performance with "as little movement as possible" with no mention about how to play the expression – could be interpreted differently by performers in this study.

We first used PCA to determine what body part stood out in terms of the amplitude differences between the expressive conditions for each excerpt. Similarly to Davidson [61], we showed that the head QoM, both along the x-axis and y-axis, was a determinant parameter that characterized each performance condition. Moreover, the head QoM was significantly different between the performance conditions at specific areas in the score, suggesting that head motion is intrinsically connected not only to the level of expression, but also to the structural elements of a piece. These results were similar to MacRitchie and colleagues [157], Thompson and Luck [232] and Teixeira and colleagues [230]. We also found that the musical excerpts can have an influence on pianists' movements closer to the keyboard. For instance, one pianist's amplitude of the hand motion along the z-axis (up and down movement) varied more than the head between the conditions for the Sonata, whereas for the performances of the Impromptu of another pianist, the amplitude of the elbow movements changed the most between the conditions.

Several studies have put in evidence the role that the vestibular system plays in the auditory encoding of rhythm, which can be activated by the movements of the head [188–190, 239]. Indeed, the head motion, which is detected by the vestibular system, can help disambiguate complex rhythms and influence the auditory perception of the metrical structure. When the body is tilted, vestibulospinal reflexes are triggered to maintain the balance of the body [13]. These reflexes are linked to postural muscles of the body, suggesting that an immobilization of the head may affect postural control and the synchronization of sensory-motor actions associated to the perception of rhythm. This could also explain why pianists' head, or the clarinet bell, moves accordingly to the rhythmical structure of pieces, mainly those with constant rhythmic patterns. In our study, pianists' movements were not physically blocked but only consciously suppressed. Even in an immobile condition, the pianists in this research were unable to remove completely the head movements, which would have disrupted too much the natural expression in their performance. This is also similar to Wanderley's results for clarinetists' performances and the movements of the bell [251].

By looking at the recurrent movements between a group of pianists, our intention was to visualize where exactly in the score do pianists tend to move in a similar way. Recurrent head movements were found in specific regions of the score, such as passages with large arpeggios and a chordal texture for the Sonata, and modulations and moments of rest in between two chromatic melodies for the Ballade. This reveals that even body parts with more degrees of freedom such as the head, and with more expressive possibilities, are inherently connected to the musical structure. The correlation map for the Impromptu also showed that very few and short passages in the excerpt were marked with recurrent head movements, suggesting that this type of writing allows pianists to play with more idiosyncratic movements. We can infer that during these moments, the movements are either strongly dependent on the musical structure or on the physical constraints of the instrument.

Wanderley [249] and Teixeira and colleagues [230] also found that different standing clarinetists perform a piece with similar body movements in specific areas of the score, such as phrase boundaries. Subsequently, it was found that recurrent patterns of clarinet bell motion occurred simultaneously with expressive timing modifications [231]. Moreover, although there were consistencies in body motions, it was shown that clarinetists performed the piece with idiosyncratic amplitudes and velocities of movement [175], and that performers could be grouped based upon the body regions they used to perform the conditions [252]. Weiss and colleagues [255] classified clarinetists' performing style on the basis of different motion types related to the amplitude of movements from the arms or knees. These findings suggest that, in addition to having a solid representation of musical structure, performers also conceive the different structural levels of a piece in a similar way and add their personal ideas by varying the finer details of structure. This information can be used in piano lessons as a point of departure for beginners in order to help them progressively develop their personal expression.

We looked at how structural parameters of different pieces of music from the same repertoire may influence pianists' expressive possibilities and the quantity of body motion. In our study, the technical difficulty and structural features characterizing each Romantic excerpt had an impact on pianists' amplitude of motion when performing each condition. For instance, the Sonata contains larger variations in dynamics, articulations, thematic motives than the two other excerpts, and these parameters were mainly accentuated during the exaggerated performance by variations in amplitude of motion. The Ballade's complexity (i.e. few rests, high speed, polyrhythm and chromatic melody) prevented pianists to exaggerate their movements, whereas it was easier to do so in the Sonata. Although pianists found almost effortless to perform the immobile condition for the Ballade, we could still perceive periodic head movements which were synchronized to the constant rhythm at the left hand. This is interesting because Wanderley and colleagues [252] found that clarinetists' motion of the bell was phrasing-oriented or rhythmic-oriented. This suggests that musicians may align their movements with the rhythmic motives of phrasing patterns in the piece and modify their timing accordingly, and that even when reducing the quantity of body movements, musicians may not be able to suppress entirely the movements that are driven by rhythm. The melodic and rhythmic simplicity of the Impromptu excerpt allowed pianists to play the conditions with large variations in head QoM during the exaggerated performance, mainly at the beginning of the melody of the main theme and at its return. These results are somehow different from Weiss and colleagues' findings [255], showing that clarinetists' movements were not significantly affected by pieces of different styles, as specific motion types for each clarinetist (e.g. predominant knee motion or arm motion) were used for all the pieces.

Finally, the survey provided additional information on whether pianists are aware of the way they use body movements in relation to the musical structure, the levels of expression and QoM. Pianists' answers revealed that the technical complexity of the Ballade excerpt may have prevented them from playing with exaggeration without perturbing the flow of the performance. This is similar to Wanderley and colleagues' findings [252], where clarinetists stated that playing with excessive motion when standing can lead to a tensed performance, and therefore may disrupt the technical precision required. This may be explained by the fact that, during an exaggerated performance, the frequency of oscillations of clarinetists' body movements increased as compared to a normal performance [55]. Pianists also observed that they considered the arms' movement and weight to be essential parameters to communicate the desired expressive ideas and that consciously immobilizing certain movements felt unnatural and destabilizing which prevented them to perform with the appropriate sound expression. In spite of this, one pianist still mentioned that by restraining certain movements, special attention was put on listening to the performance instead. That pianist has had difficulties in the past when trying to adopt an adequate posture while performing, putting too much emphasis on the movements instead of the sound. That condition actually helped her remove the tension she felt while trying to adjust her movements and helped her focus more on the desired acoustic results. Consciously immobilizing the movements could potentially be useful during instrumental lessons with students who struggle to connect body movements and musical expression.

7.3 Auditors' ability to discriminate between expressive conditions

The results from the exploratory study revealed that, on average, auditors are better at discriminating the performance conditions with both auditory and visual information, which diverges from Davidson's results [60, 61], but is similar to Vuoskoski and colleagues' findings [248]. It was easier for auditors to recognize the conditions through auditory information only for two pianists, which suggests that either the pianists or the excerpts they performed helped auditors discriminate correctly between the performances. We also found that auditors were not able to discriminate between the deadpan and immobile conditions above chances when being provided with visual information only, and the same occurred between the normal and immobile conditions in the audio modality. These results converge with Nusseck and Wanderley's findings [175], which showed that suppressing certain kinematic features from the performance, such as the movement of the torso or the arms might not change auditors' perception of acoustic parameters.

Previous research has demonstrated that visual information contained in a musical performance can influence the perception of different expressions even more than audio information alone [34, 54, 61, 245, 248]. Indeed, when two sensory inputs come from the same environmental event, people will be more likely to connect them (e.g. [123, 257]). However, when attention is drawn away from an auditory event by having a visual stimulus, the auditory cortex indicates a decreased activity in response to the auditory information [130]. It is possible that removing auditory information from a musical performance can help discriminate between different expressive conditions, as Davidson showed that auditors were better at discriminating between expressive conditions with the visual information only [61]. Similarly, it was also found that the visual information contained in clarinetists' exaggerated performances allowed auditors to discriminate them from a normal performance or an immobile performance [49]. Interestingly, when seeing the performances only, auditors judged the immobile performances as more interesting musically and visually than the exaggerated rendition of the piece.

In our study on audience perception, we have shown that suppressing certain movements can affect pianists' internal representation of the structural organization of the music, such as the phrasing structure, the perception of timing, and the sound dynamics. This may explain why auditors noticed these variations between the two conditions. By specifically analyzing two pianist' normal and immobile performances of the Sonata and the Ballade, we were able to investigate the perceptual influence of the two conditions, one with a natural amount of movements and the other with restrained body movements. Our study showed that the ability to discriminate a natural performance from a performance with restricted movements is influenced by both the pianist's play and the type of musical excerpt, which is partially against Vines and colleagues' results [245], who found that auditors could not discriminate between the performance conditions (i.e. restrained, standard, exaggerated) when listening to clarinet performances only. In the current study, auditors rated timing and phrasing as the most important auditory parameters for both pianists to discriminate a normal performance from an immobile one, which is aligned with earlier results from studies that evaluated listeners' ability to sort musical performances [92, 146, 203, 246]. We also showed that auditors did not rely on articulation, which contradicts Gingras and colleagues' findings, who found that listeners focus their attention on tempo and articulation to recognize different performances of the same piece being performed by the same performer [92].

7.4 Effect of the immobile condition on movement and sound features

In addition to analyzing the acoustic differences when pianists perform in an immobile condition, we also measured specific movement parameters. We found that pianists may adopt a very different playing style when consciously immobilizing certain movements. For instance, one pianist significantly reduced the acceleration of the hand during the Ballade, whereas it was not the case for the Sonata. While the acceleration of the head and torso was significantly different between the two conditions for both pianists and musical excerpts, certain dissimilarities were observed between pianists. Pianist 2 reduced significantly the QoM from the upper body, as well as the arms and hands for the Sonata, whereas pianist 1 did not. These findings reveal that, for certain pianists, even a slight modification in movements, such as the amplitude or acceleration of head motion, can influence the sound parameters in a way that is noticeable for musically trained auditors. It is possible that asking pianists to suppress certain body movements while performing can affect their structural representation of music, and possibly more so for certain Romantic pieces such as the Sonata.

We found that the key velocity, a measure that represents well the sound dynamic, differed significantly between the two conditions for both pianists and excerpts. Results from Chapter 4 showed that pianists' overall durations of performances did not differ significantly between a normal and immobile conditions. However, in Chapter 5 we showed that, when grouping the values per phrase instead of considering each individual note, timing (IOI) was the only parameter that generated significant differences between the conditions for certain areas of the score, such as loud accentuated chords and large arpeggios.

To clarify the relationships between movement and audio features, correlation analysis was used in Chapter 5. Similarly to what Camurri and colleagues [28] described, head velocity and key velocity were highly correlated for both pianists and mainly for the Sonata. For the Sonata, small IOI was related to larger head and torso motion, while for the Ballade, slower movements were associated to an increase in sound dynamics, mainly for pianist 1. It was also demonstrated by Shoda and Adachi [220] that variations in amplitude of movement were correlated to temporal manipulations. For instance, in fast pieces with a steady beat, the body moves before lengthening the note in a slower passage.

Finally, our findings highlighted the fact that a close link exists between sound and motion parameters in piano performance: even body parts that are less implicated in the production of the sound, such as the head and torso, can have an effect on the expressive results, both perceptually and acoustically.

7.5 Postural sway in different performance conditions

To study the mechanics of movements during piano performance, Chapter 6 investigated the kinetics of the performances of the Sonata, the Ballade and the Impromptu, yielding meaningful information regarding how experienced pianists control their posture while playing in different performance conditions. First, it was demonstrated that it is essential for pianists to be able to control different kinetic parameters simultaneously with postural movements to communicate efficiently the structural characteristics of a piece, as well as the desired expressive intention. We found that kinetic parameters alone, such as the medial-lateral COP displacement and vertical force, could characterize each excerpt. However, postural angles differed between the Sonata and the Ballade, but not between Ballade and Impromptu. The Sonata and the Ballade were different from the Impromptu in terms of ML COP displacement and velocity of COP displacements. This might be explained by the fact that the Ballade and the Impromptu differ greatly from each other in terms of the rhythmic structure and melodic and harmonic form.

Pianists' COP displacement in the ML direction was more disturbed by a modification in the level of expression, such as in the deadpan or exaggerated conditions. As proposed Cholewicki and colleagues [35], postural control can be more easily achieved in the anterior-posterior direction, by using the support and force of the legs, even when postural angles in the same direction vary in a significant manner between the conditions. We also showed that the movements of the spine, namely the neck, torso and hip motion, work in a very connected manner in pieces with abrupt postural changes and high sound energy (i.e.

variations in articulation, dynamic and texture), as found in the Sonata.

We demonstrated that performing a piece while trying to reduce certain movements and trying to reproduce a natural expression did not affect postural stability, whereas exaggerating the musical expression had an effect on the postural sway. Previous research have shown that pianists use larger QoM when performing in an exaggerated manner in specific areas of the score [220, 232]. In Chapter 4, we also revealed that pianists modulate the amplitude of movements in pieces that are less demanding technically, which is also aligned to Wanderley and colleagues' results [252]. This is interesting because in Chapter 6, we showed that pianists' COP displacements were larger during an exaggerated performance as compared to all the other conditions, for the Sonata and the Impromptu, but not for the Ballade. This means that exaggerating the acoustic parameters up to a certain point, in excerpts that allow pianists to do so, may be detrimental to pianists' postural stability. In the survey from Chapter 4, pianists mentioned that playing in an immobile manner felt destabilizing, particularly during the performances of the Sonata and the Impromptu, whereas they thought it was almost impossible to exaggerate the sound for the Ballade without disrupting too much the flow of the performance and accuracy of the rhythm and notes. Although pianists found it difficult to perform while reducing certain body movements, their movements were not physically blocked, such as in Rozé's research [210], in which cellists' postural control was disrupted. Rozé also found that in a physically immobilized condition, cellists' head and torso were forced to oscillate together and more rapidly than the bow strokes, which resulted in greater force variations and larger COP displacements. Nevertheless, as shown in Chapter 5, when pianists consciously immobilize their movements, the postural stability does not appear to be impaired, but seem to affect certain acoustic parameters, such as sound dynamic and timing.

Biomechanical studies have shown that the sitting posture increases forward inclination of the head, caused by forward flexion (head closer to the ground) and anterior translation (torso moves forward), which in turn may accentuate tension on the cervical spine [115]. Several physical problems also result from a forward head posture, such as an increase in cervical curvature, an alteration in the thoracic kyphosis, or again downward rotation of the scapula. Pianists can achieve a better postural control when the whole body is implicated in the movement, which may lead to a reduction in muscle tension acting on the neck and spine.

Although the relationship is stronger for the Sonata and the Impromptu, our results revealed that the upper body angles used in the AP direction have a strong correlation with vertical force no matter the excerpt being performed. We also found that pianists use the force of their legs in energetic passages, which may help them communicate better structural and expressive ideas, and potentially prevent injuries when using large swaying motion towards and away from the keyboard. Indeed, an optimal positioning is conditioned by the relationship between the legs and the pelvis, which helps transfer the effort from the legs to the upper body and arms [88], while a complete immobilization from the pelvic region may cause rigidity in the legs.

Chapter 8

Conclusion

8.1 Contributions

This research provided new knowledge regarding the types of strategies experienced pianists use to convey their expressive intentions and interpretation of the musical structure through body movements. The combination of kinematic and kinetic analyses by means of motion capture and force-plate technologies shed light on individual and shared artistic communication skills in piano performance, and the musical decisions that pianists make, physical and acoustical, to deliver expressive messages. In addition, the multimodal analysis conducted on audience perception provides a better understanding of the relationships between pianists' musical intentions and listeners' perceptual reaction. By studying perception of musical performance, new insights was provided regarding the fundamental processes in human communication and the associations formed between sensory, affective and motor processes. Finally, using different Romantic excerpts with the same group of expert pianists has shown that performers' expression and body movements depend on their understanding of the musical structure, and that results from previous research should therefore not necessarily be generalized to a particular musical style.

Chapter 4 has demonstrated the importance of examining various pieces from the same Repertoire with the same group of participants. Indeed, we showed that the technical difficulty characterizing each excerpt had an important effect on pianists' capacity to modulate the QoM during each performance condition. We demonstrated that even body parts with more degrees of freedom and more expressive possibilities, such as the head, are inherently connected to the musical structure. Moreover, recurrent head movements across a group of experienced pianists can be observed in specific areas of the scores. These findings suggest that, in addition to having a stable representation of musical structure, pianists conceive the different structural levels of a piece in a similar way and add their personal ideas by manipulating the finer details of structure. This information is important for the field of piano pedagogy, as it can provide more systematic feedback in instrumental lessons to help students transfer teachers' explanations to various musical contexts and make independent creative choices regarding body movements. By acquiring more data on pianists' body movements during playing of different musical pieces of varied repertoire, one could possibly generalize the results to different musical contexts while considering the stylistic features of the piece, its structural elements and technical challenges. Indeed, this could lead to a better understanding of the categories of movements that students may use to convey different expressions associated to the structural parameters, the technical difficulty and physical constraints brought by the instrument.

We have shown in Chapter 5 that the ability to discriminate a natural performance from a performance with restricted movements is influenced by both the pianist's performance and the musical excerpt. Furthermore, even a slight modification in pianists' movements can influence the sound parameters in a way that is noticeable for musically trained auditors, and that the parameters more susceptible to be affected are the sound dynamics and phrasing. Few studies have evaluated the ability of humans to process acoustic cues in music performance. To our knowledge, this study is the first empirical research that evaluates auditors' ability to accurately discriminate between performance conditions, while comparing physical and perceptual data results. We also underlined the fact that the musical excerpt may exert an influence on the QoM and posture required to perform with the desired expression.

The results from Chapter 6 demonstrated that the writing style of different Romantic pieces, as well as the expressive intention of the performers, can affect pianists' postural sway. In fact, playing as naturally as possible while reducing the movements did not affect pianists' postural control, whereas exaggerating the sound parameters had an influence on the COP displacements, mainly for the Sonata and the Impromptu. Changes of postural angles in the ML direction were associated to pianists' COP displacement along the same direction, whereas AP movements were connected to changes in force applied on the stool. Research on the biomechanics of piano playing and pianists' postural control strategies can help teachers integrate recommendations related to the posture of the whole body in relation to the musical structure and expressive intentions.

Overall, the findings from this research have led to a better understanding of the musical decisions that pianists make, in terms of physical and acoustical outcomes, to convey the expressions of different Romantic pieces. We have shown that some movements are essential to perform parameters related to the rhythmic structure and sound dynamics, that posture can be described as a relationship between body angles and kinetic features, and that changing the quantity of movement can have an effect on the auditory perception and sound results.

Piano pedagogy includes theories related to weight-playing [119], finger articulation [178], as well as concepts to avoid injuries [83, 212] and adopt a proper posture [136, 253]. Somatic training techniques such as the Alexander technique or the Feldenkrais method may also help musicians develop movement awareness. By integrating the various pedagogical approaches, biomechanical concepts and scientific results on the relationships between movements and musical contexts, instrumental pedagogues could use strategies that are more intuitive in terms of expression and its link to body movements, healthy posture and musical structure.

Despite the fact that many students will not reach a professional level [65], musical expression, body movement and posture, as well as pianists' active listening to their own performances, should receive more attention during piano lessons. Unfortunately, there are still conflicting methods in the way piano is taught, which can create confusion for students learning how to tackle the physical aspects of piano performance, especially if they are changing teachers throughout their musical training. Although different teaching methods can stimulate the student's creativity by providing new artistic ideas, music pedagogy still suffers from a lack of explicit theories that could guide the teaching of expression [137] and posture [211]. Incorporating a science-based pedagogical approach in piano pedagogy can lead to the design of a coherent pedagogical framework that can improve the quality and accuracy of teachers' feedback by helping students become aware of the effect of movements on the sound and on audience perception.

8.2 Limitations and future work

The purpose of this thesis was to investigate the relationships between pianists' body movements, musical expression and structural parameters of different pieces from the Romantic period, and to examine the perceptual influence of body movements on auditors' judgments of these performances. The main challenge when combining such contrasting research interests (i.e. performers' body movements, auditors' perception, audio parameters) was first, to find a common way to analyze and put in relation these various parameters and second, to use measurement methods and equipment that did not affect the ecological validity of the results. Consequently, certain limitations need to be acknowledged.

The disadvantage with human motion analysis systems is a trade-off between accuracy and ecological validity of the measurement. For instance, it was not possible for us to set the infrared motion capture systems in a performance environment. Therefore, the experiment had to happen in a laboratory setting, with a digital piano. This does not correspond to the traditional practice environment of a pianist nor does it correspond to the instrument on which pianists commonly perform.

At the end of the measurement session, pianists were asked whether the experimental procedure limited their performance in any ways, and they acknowledged the fact that the digital piano prevented them from playing with all the nuances they would have normally used on an acoustic grand piano. The mechanics of a piano allow pianists to feel the only contact point with the strings, and provide them with accurate control over the speed at which the hammer strikes the string [101, 103]. The complex key action mechanisms give pianists control over a wide range of sound dynamics and onset timing. A more detailed and accurate control of key action can potentially be achieved through a better feel of the hammer [144]. Experienced pianists are usually well acquainted with the temporal actions of an acoustic piano, which they use intentionally to perform expressively.

Digital pianos have the advantage of built-in MIDI input and output which makes it possible to collect measurements of timing, key velocity and articulation. It would have been preferable to use a computer-controlled grand piano to measure additional expressive parameters, such as maximum hammer velocity, maximum key depression angle, sustain and soft pedals use during the note, as well as their duration and amount of depression [11, 101]. Although the reflections on the surface of an acoustic piano may cause artefacts in the data, further research should replicate the study on Grand piano-embedded CEUS digital recording systems, such as the Disklavier and the Bösendorfer SE system. In addition, these pianos could improve the ecological validity of the results, since they produce a measurement close to a keypress motion required for acoustic pianos.

Another potential limitation concerns the fact that participants were video and audio recorded during the experiment. Even if they were informed before participating, it is possible that, to some extent, their performance was affected by the situation. Although participants were experienced pianists who may have been previously recorded during their training, for instance during an exercise in a masterclass, the setting and demands were probably confusing to them [261].

In this study, a small sample of Romantic musical excerpts was used. At this stage, only preliminary results were presented to serve as a basis for further research and pedagogical recommendations. Considering the fact that the piano repertoire is very vast, it would be important to acquire more movement data from a larger sample of pieces from different musical styles. Future recommendations based on scientific results need to be adapted to the specificity of each musical context. Therefore, a common database should be implemented for data sharing between researchers working on the movement in music performance. Already existing databases can also be considered, such as the Musical Motion Database [99] or Repovizz [163], used for exchanging and visualizing multimodal data and results for collaborative research purposes.

While the qualitative analysis of pianists' answers proved to be insightful, the survey did not provide information regarding the structural analysis the participants would have themselves conducted for the different pieces. Their personal analysis and segmentation of the phrasing, rhythmic, melodic and harmonic structure, for instance, could have helped interpret better the quantitative results related to each of their performances. For instance, we could have compared the variations in timing, sound dynamics, articulation, and amplitude of motion to their structural analysis to understand how these crucial points in the score, that may be analyzed and interpreted differently across performers, may affect musical expression and body movements.

Principal Component Analysis (PCA) and Canonical Correlation Analysis (CCA), as used in Chapters 4 and 6, have been shown to be powerful methods to eliminate any redundancy in a large data set [2, 226] or to measure the strength of association between two set of variables [219]. They can be effective in motion analysis [235], and when applied to motion capture data, can describe the musician's global dynamic motion [237]. However, these analysis methods also have their limitations. Recent studies have discussed the disadvantages of using PCA [77, 180]. For instance, the interpretation of the results must be taken cautiously, as we do not know a priori how the variables are related and how they covary. The components are measured using all of the variance of the variables, and the data needs to be normalized because the analysis is sensitive to extreme values in the data sets. Moreover, canonical functions refer to the linear relationship between variables, meaning that CCA cannot exhibit non-linear associations between sound and movement features for instance [32]. In addition, although the number of variables can vary in the two sets being compared, a finite number of parameters must be previously selected, which means that the information contained in the movement and sound signals is incomplete.

Functional Data Analysis (FDA), a statistical method that represents each curve as a function and explains how data changes continuously over time [195], could be a good solution to study how body movements happen over a period of time, instead of using discrete values, such as the average, maxima or minima, which eliminate a certain amount of essential information. With FDA, one would be able to measure important information in continuous signals, such as changes in joint angles or landmark positions during a movement task, instead of considering only each individual moment. Moreover, functional analysis of variance (FPCA) can then be used to measure how much the pattern of amplitude variation is attributable to each performance condition or excerpt, and what moment in time can best explain this variability.

Throughout the research, we focused specifically on how pianists would diverge in terms of movements and expression when performing pieces from the same repertoire. We did not investigate whether a different style would produce similar or different results across different pianists. This work could be expanded by looking into the impact of pieces from various periods on pianists' movements and acoustic features when playing in different expressive conditions. Research on music education faces problems because of the lack of consideration for individual differences in students [45]. Therefore, additional work is also needed to identify whether there exist distinct groups of pianists who tend to perform with similar body movements, and whether these groups are influenced by their individual musical formation, cultural background and pianistic style.

Some issues must be raised about Chapter 5. First, as we wanted to examine the effect of individual pianists' movements on specific acoustic features, the analysis must be interpreted carefully. The sample size of two pianists and two excerpts was too small to provide concrete evidence of the effect of the pianist and the musical excerpt on auditors' ability to discriminate between a normal and immobile performance conditions. Another limitation of this study lies in the fact that, when asked to rate how each of the acoustic parameters helped discriminate the conditions, auditors mentioned that it was difficult to dissociate the concepts of 'phrasing' and 'timing'. A clearer explanation of each parameter and their respective meaning in the context of our study would probably have helped auditors make more accurate judgments. Moreover, it is also possible that auditors coming from different cultural and musical backgrounds (i.e. other than Western classical music) can perceive musical expression in a totally different manner. In our study, auditors' ability to discriminate the conditions was not affected by the musical style they were trained in. Although they performed in different styles other than classical music (e.g. rock, jazz, pop, afro-cuban), they were still all exposed to Western music and theory. Further studies should focus on the effect of various cultural backgrounds on auditors' perceptual reaction to classical music, expression and performers' body movements.

Although this study has shed light on the ability of humans to process audio information in music performance and how pianists' body movements may influence the communication of these audio cues, it also leaves some questions unanswered. For instance, even though we have shown that a pianist's performance could be recognized on the basis of changes in sound features created by a slight modification in amplitude of body motion, it remains to be clarified how an exaggerated expression with natural body movements would influence auditors' visual experience. The effect of different performance conditions on perception should be investigated through continuous ratings of tension and arousal (e.g. [154, 246]).

As this research examined more specifically the common patterns in a group of experienced pianists, further studies should also consider the individual strategies that pianists employ to explain better idiosyncratic movements, as well as the link with structural characteristics. Each pianists' body characteristics should also be measured and considered separately. Anthropometric data (i.e. height, weight, sex, age, segment length, location of mass centers, etc.) can provide essential information regarding the differences in individuals and groups [265]. In the context of piano performance, postural control can be affected by pianists' physical characteristics when playing with various levels of expression or QoM, as it was shown that anthropometric variables can influence the degree of variation in COP displacements [35]. More research is also needed to study the effect of different levels of expression on pianists' muscle activity by using EMG. Combining anthropometric and EMG data with kinematic and kinetic measurements could help study the relationships between these characteristics depending on the musical context. For instance, it could be interesting to determine what movements are considered healthy and how muscular control varies across individual pianists according to their physiological characteristics.

Appendix A

List of Hardware and Software Components and Functions

The organization and functions of the hardware components used for the experiments presented in this thesis are described in Figure A.1 and Table A.1. All digital and analog devices were synchronized and time stamped. The network connection ensured the synchronization of the various data streams (e.g. motion capture, force plate, video, audio and MIDI recordings). The absolute time stamping was implemented by the SMPTE clock generator (Rosendahl Nanosyncs HD). The software components and their functions are summarized in Table A.2.

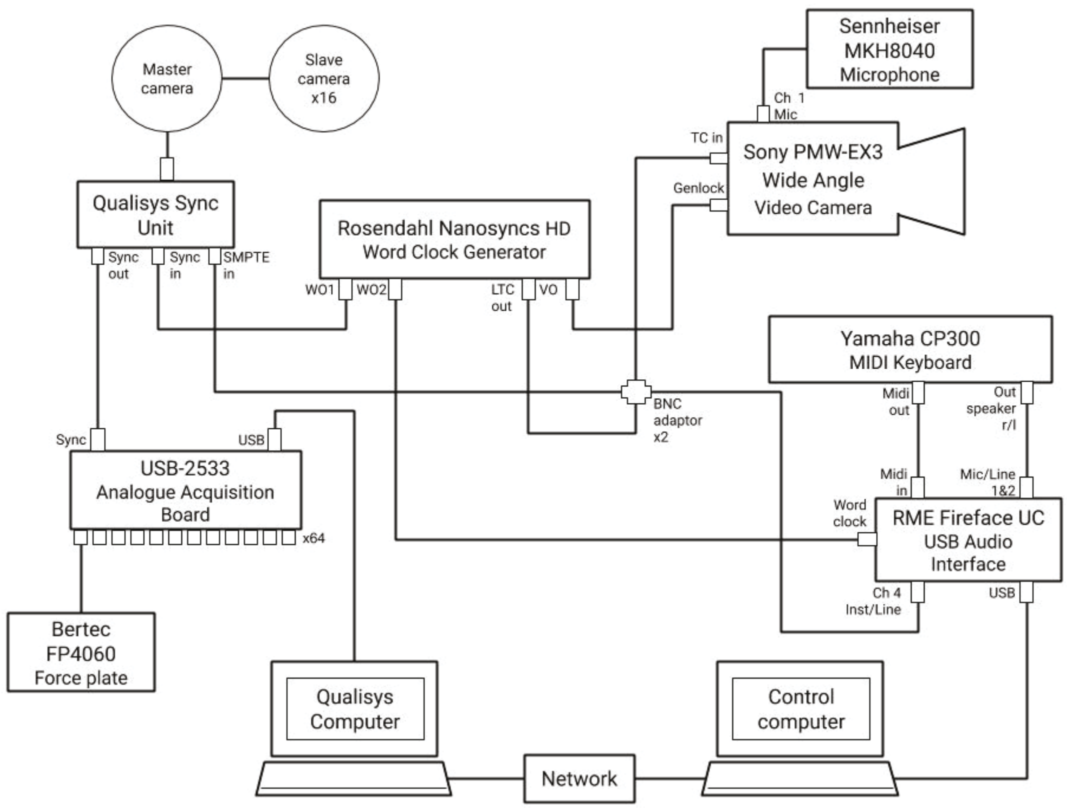

Fig. A.1 Hardware wiring scheme. The Rosendahl Nanosyncs connects to the video camera, the Qualisys Sync Unit, and the Fireface audio interface. The Qualisys Sync Unit converts the SMPTE signals so that it can be measured by the mocap cameras. The control computer records the audio and MIDI from the MIDI keyboard with Reaper software and is connected to the same network as the Qualisys computer, which triggers with OSC protocol the recordings of both QTM and the audio/MIDI from the keyboard.

Table A.1 List of hardware components and functions

HW Component	**Model**	**Function**
Motion capture cameras	17 cameras (6 Oqus 300 and 11 Oqus 400)	Infrared cameras for marker acquisition
Video camera	Sony PMW-EX3 Wide Angle	Video capture
Microphone	Sennheiser MKH-8040	Audio recording
Camera Sync Unit	Oqus Sync Unit	Synchronize Qualisys cameras and video camera with word clock
Word clock	Rosendahl Nanosyncs HD	Clock synthesizer
Qualisys computer	Mac Pro with Boot Camp partition (Windows 7)	Record and process Qualisys motion data
Force plate	Bertec FP-4060	Forces and moments recording
Analog acquisition board	USB-2533	Multifunction measurement and control board to synchronize the mocap and analog data
Control computer	MacBook Pro 2011	Audio and MIDI recording from MIDI keyboard with Reaper software
Piano keyboard	Yamaha CP300	MIDI recording
Audio interface	RME Fireface UC USB	Input and output of audio signals

Table A.2 List of software tools and functions

SW Component function	**Name**	**SW release / OS**
Motion capture system	Qualisys Track Manager (QTM)	V 2.12 (build 2570) / Windows 7
Video processing	Final Cut Pro	V 10.3.3 / MacOS Sierra V 10.12.3
DAW for audio and MIDI recording	Reaper	V 5.965
MATLAB	Mathworks	R2016
Mocap data analysis library (for Matlab)	MOCAP toolbox	V 1.5 (2015)
Audio editing	Audacity	V 2.1.0
OSC protocol	QTM Real-time Server Protocol	V 1.17
Connect QTM and Reaper	Max/MSP Cycling '74	V 7.3.5

A.1 Synchronization protocol

Each digital device has an internal clock that sets the timing of its signal, and that runs at the speed of the pre-determined sampling rate for the audio stream [19]. When the experimental design involves large capture setups and the simultaneous measurement of several parameters (i.e. motion capture, force data, sound parameters (MIDI and acoustic) and video), it is imperative to synchronize all devices to avoid that they run at marginally different rates, causing drift, and thus loosing frames and information.

There exist various digital audio transmission protocols, but they are essentially based on the same idea. The signal is transmitted as a stream of small frames of data that contains the audio sample accompanied with timing, channel information, and error correction bits. If the stream is divided at the wrong location, the data frame is invalid. When the device receiving the digital audio stream has a word clock running in sync with the word clock of the device sending the digital audio stream, each frame that is transmitted is received and interpreted accurately.

A.1.1 Word clock

One of the synchronization strategies is to use an external timecode unit to ensure that all devices follow the same timecode and to create a robust wireless sync network [19]. External hardware specifically designed for that purpose are likely to be reliable and precise. For instance, a word clock generator, such as the Rosendhal Nanosync, has a well-regulated word clock signal, and several output connectors to send that signal to all the digital devices in the system. Moreover, it can generate and sync to other synchronization signals, such as MIDI Timecode (MTC) (i.e. translation of an SMPTE time code signal into a MIDI standard time code signal), Linear Timecode (LTC), and video signal. If the word clock generator has several outputs, it can be connected to each device.

A.1.2 SMPTE

SMPTE timecode, an acronym for the Society for Motion Picture & Television Engineers, was used to timestamp the beginning of each measured frame. It is recorded as an audio signal that can be read by many devices, such as MOTU audio interface or Rosendhal Nanosync word clock. When MIDI is recorded from a digital keyboard, synthesizers or Digital Audio Workstation (DAW) software can be used, which will translate the timecode into MTC. MTC can be generated by most DAW software (e.g. Logic or Ableton). LTC is an encoding of SMPTE timecode in an audio signal. This audio signal can be recorded on a separated track to ease the postprocessing segmentation.

QTM can record video, audio and analog data together with the motion capture data, using synchronization protocols. When using an external timebase, such as the Nanosync Word Clock, it is recommended to employ a multiple of the SMPTE signal as camera frequency. Finally, to be able to compare the audio data with the Qualisys data, the audio sequencer should record the SMPTE timestamp.

The audio clock phase can be adjusted to the video phase. Therefore, the video's beginning of picture will be phase locked to the word clock signal. The Oqus sync unit will convert the SMPTE signal so it can be read by the mocap cameras. When using SMPTE for time-stamp, as well as another external signal, provided by the Word clock for instance, it is important that both devices are connected to the same master camera. The sync out signals are used both for synchronizing the analog board and the mocap cameras. By default, the signal sends a pulse for each camera frame where the pulse has the same length as the exposure time.

Appendix B

Motion Capture Camera Settings and Marker Placement

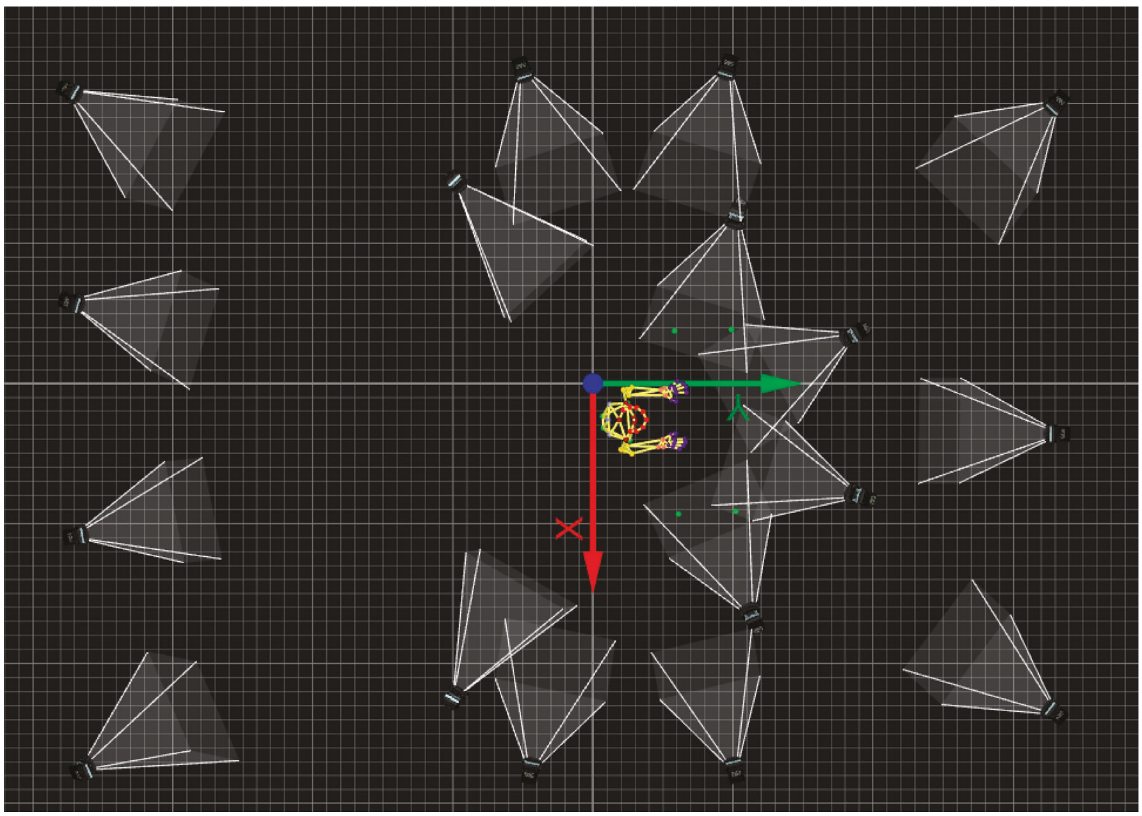

Fig. B.1 Motion capture camera placement in Qualisys Track Manager (QTM). An example of the mocap-skeleton of one pianist is shown and the 3D coordinate axes.

Fig. B.2 Laboratory setup. Motion capture cameras, MIDI keyboard, force plate, video and audio recording are visible.

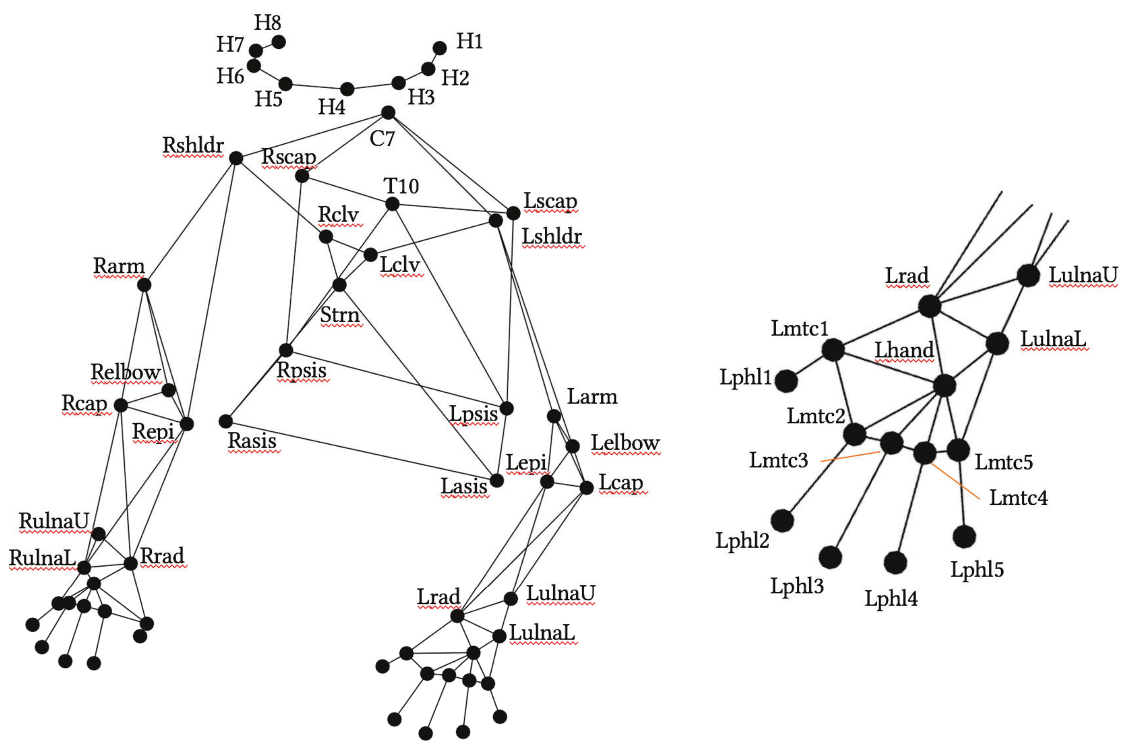

Fig. B.3 Reflective marker placement and labels used for the motion capture data analysis. The full names for each marker are displayed in Table B.1 below.

Table B.1 Description of the Plug-in-Gait markers (continues on next page)

Head Markers	
H1	Head 1
H2	Head 2
H3	Head 3
H4	Head 4
H5	Head 5
H6	Head 6
H7	Head 7
H8	Head 8
Torso Markers	
C7	7th cervical vertebrae
T10	10th thoracic vertebrae
Rclv	Right clavicle (jugular notch)
Lclv	Left clavicle (jugular notch)
Strn	Sternum (xiphoid process)
Rscap	Right scapula
Lscap	Left scapula
Arm markers	
Rshldr	Right shoulder (acromio-clavicular joint)
Lshldr	Left shoulder (acromio-clavicular joint)
Rarm	Right upper arm (between shoulder and elbow markers)
Larm	Left upper arm (between shoulder and elbow markers)
Relbow	Right elbow (above joint)
Lelbow	Left elbow (above joint)
Rcap	Right capitulum of humerus
Lcap	Left capitulum of humerus
Repi	Right medial epicondyle of humerus
Lepi	Left medial epicondyle of humerus
RulnaU	Right upper ulna
LulnaU	Left upper ulna
RulnaL	Right lower ulna (wrist joint pinkie side)
LulnaL	Left lower ulna (wrist joint pinkie side)
Rrad	Right radius (wrist joint thumb side)
Lrad	Left radius (wrist joint thumb side)

Hand markers	
Rhand	Right hand (middle hand)
Lhand	Left hand (middle hand)
Rmtc1	Right metacarpophalangeal joint (thumb)
Rmtc2	Right metacarpophalangeal joint (index finger)
Rmtc3	Right metacarpophalangeal joint (middle finger)
Rmtc4	Right metacarpophalangeal joint (ring finger)
Rmtc5	Right metacarpophalangeal joint (pinkie)
Lmtc1	Left metacarpophalangeal joint (thumb)
Lmtc2	Left metacarpophalangeal joint (index finger)
Lmtc3	Left metacarpophalangeal joint (middle finger)
Lmtc4	Left metacarpophalangeal joint (ring finger)
Lmtc5	Left metacarpophalangeal joint (pinkie)
Rphl1	Right phalangeal joint (thumb)
Rphl2	Right phalangeal joint (index finger)
Rphl3	Right phalangeal joint (middle finger)
Rphl4	Right phalangeal joint (ring finger)
Rphl5	Right phalangeal joint (pinkie)
Lphl1	Left phalangeal joint (thumb)
Lphl2	Left phalangeal joint (index finger)
Lphl3	Left phalangeal joint (middle finger)
Lphl4	Left phalangeal joint (ring finger)
Lphl5	Left phalangeal joint (pinkie)
Lower body	
Rasis	Right anterior superior iliac spine
Lasis	Left anterior superior iliac spine
Rpsis	Right posterior superior iliac spine
Lpsis	Left posterior superior iliac spine

Appendix C

Musical Excerpts

1. Medtner Sonata Reminiscenza Op.38 (mes. 253-274)
2. Chopin 4th Ballade (mes. 152-160)
3. Chopin Impromptu (mes. 43-51)

Fig. C.1 Medtner Sonata Reminiscenza Op.38 (mes. 253-274)

Fig. C.2 Chopin 4th Ballade (mes. 152-160)

Fig. C.3 Chopin Impromptu (mes. 43-51)

Appendix D

Questionnaires and Task Instructions

D.1 Background questionnaire for auditors

1. Age:

2. Gender (circle): female - male - other - prefer not to disclose

3. Where did you receive your musical formation (school, university, country)?

4. What instrument(s) do you play?

5. In which style(s) were you trained in (e.g., classical, jazz, popular, rock)?

6. What is the highest degree or level of school you have completed? If currently enrolled, highest degree received.

    - College
    - University (undergraduate)
    - University (graduate)
    - Other

7. How many years of musical training do you have? From (circle):

    0 to 10 - 11 to 20 - 21 to 30 - 31 to 40 - more than 40

8. How many times per year do you perform? From (circle):

    0 to 15 - 16 to 30 - 31 to 45 - 46 to 60 - more than 60

9. How many hours per week do you practice? From (circle):

    0 to 5 - 6 to 10 - 11 to 15 - 16 to 20 - more than 20

Table D.1 Auditors' answers to the background questionnaire

Auditor	Age	Gender	Musical formation
A1	24	f	B.M. vocal performance, University of NC Greensboro
A2	21	m	B.Mus. McGill, Canada
A3	25	f	Eastman School of Music, USA
A4	24	f	Us University
A5	41	m	College of Santa FE (USA)
A6	36	m	Fawldade Santa Marcelina, Brazil and UNICAMP
A7	37	m	Jordan academy for music
A8	21	f	McGill, Canada
A9	24	f	University
A10	26	m	Brandon Unversity Conservatory, McGill University, uOttawa, UdM
A11	25	m	Shepherd School, Rice University, USA
A12	23	m	McGill, Canada and USA
A13	28	m	University of South Carolina, McGill, UdM
A14	27	m	Jerusalem Academy of Music, Israel
A15	31	m	School of music and fine arts of Panama, Brazil and University of Southern Mississipi
A16	28	f	Unversity of Texas, Arlington, USA and Texag Chrsitian University, McGill
A17	22	f	Nanaimo Conservatory of Music, Canada; Oberlin Conservatory of music USA, McGill
A18	28	m	Private lessons, Mexico
A19	22	m	Private lessons, India
A20	22	m	Private lessons, India
A21	29	m	Berklee College of Music, USA
A22	23	m	Mount Royal University, Canada; Concordia, Canada

Auditor	Instrument(s)	Style trained	Degree	Years training	Times per year	Hours per week
A1	Voice, piano	Classical, musical theatre	Undergraduate	0-10	16-30	6-10
A2	Violin	Classical	Undergraduate	0-10	0-15	0-5
A3	Percussion, piano	Classical, jazz	Undergraduate	11-20	16-30	6-10
A4	Oboe, English horn	Classical	Undergraduate	11-20	46-60	6-10
A5	Bass guitar, guitar, keyboard, DMIs	Jazz, rock	Graduate	11-20	0-15	0-5
A6	Acoustic and electric guitar	Classical, brazilian music	Graduate	11-20	0-15	11-15
A7	Gutiar, piano	Classical	Undergraduate	11-20	0-15	0-5
A8	Violin	Classical	Undergraduate	11-20	16-30	0-5
A9	Cello	Classical, pop, folk	Undergraduate	11-20	46-60	0-5
A10	Cello	Classical	Graduate	21-30	0-15	11-15
A11	Double bass, voice, piano	Classical	Graduate	11-20	16-30	0-5
A12	Cello	Classical	Undergraduate	11-20	16-30	0-5
A13	Piano	Classical	Graduate	21-30	0-15	11-15
A14	Piano, flute, viola, guitar	Classical	Undergraduate	21-30	0-15	0-5
A15	Flute	Classical	Graduate	21-30	0-15	0-5
A16	Violin, viola, cello, bass, piano	Classical	Graduate	11-20	0-15	0-5
A17	Voice, piano, flute	Classical, jazz, musical theatre, popular	Undergraduate	11-20	16-30	0-5
A18	Drums, guitar, bass, piano	Pop, rock, jazz	Graduate	11-20	0-5	0-5
A19	Piano, guitar	Classical	Undergraduate	11-20	16-30	6-10
A20	Guitar	Rock	Undergraduate	0-10	0-15	6-10
A21	Drums, piano, guitar, bass	Rock, jazz, popular, afro-cuban, metal	Undergraduate	11-20	46-60	11-15
A22	Piano, trombone, laptop	Jazz, electroacoustic	Undergraduate	11-20	0-15	0-5

D.2 Task instructions for auditors

You will listen to ten performances of two Romantic excerpts, performed by two different pianists in two expressive conditions (normal and immobile). The pianists' performances may be repeated more than once. For each excerpt:

- Please associate each excerpt to the condition you think it was performed in

Then, rate on a 5-point scale:

- Your confidence level
- The importance of different audio cues (i.e. timing, sound dynamics, articulation, overall interpretation) that helped discriminate between the conditions

The excerpts and pianists are presented in random order. You will listen to each excerpt twice.

Performance 1

1. Listen carefully to the two excerpts. Please associate the musical excerpts to the performance conditions. Please select a different answer for each excerpt.

Excerpt 1

- Normal
- Immobile

Excerpt 2

- Normal
- Immobile

2. Please rate your confidence level for your answers.

	Not at all confident	**Not very confident**	**Moderately confident**	**Confident**	**Very confident**
Confidence level					

3. How important were the following audio cues in helping you associate the excerpts to the conditions?

	Not important	**Slightly important**	**Moderately important**	**Important**	**Very important**
Timing					
Sound dynamic					
Articulation					
Overall interpretation					

D.3 Background questionnaire for pianists

1. Age:

2. Gender (circle): female - male - other - prefer not to disclose

3. Where did you receive your musical formation (school, university, country)?

4. What instrument(s) do you play?

5. In which style(s) were you trained in (e.g., classical, jazz, popular, rock)?

6. What is the highest degree or level of school you have completed? If currently enrolled, highest degree received.

    - College
    - University (undergraduate)
    - University (graduate)
    - Other

7. How many years of musical training do you have? From (circle):

    0 to 10 - 11 to 20 - 21 to 30 - 31 to 40 - more than 40

8. How many times per year do you perform? From (circle):

    0 to 15 - 16 to 30 - 31 to 45 - 46 to 60 - more than 60

Table D.2 Pianists' answers to the background questionnaire

Pianist	Age	Gender	Musical formation
P1	35	f	Moscow Conservatoire, Russia
P2	36	m	Université de Montréal, Canada
P3	22	f	McGill University, Canada
P4	27	m	Université de Montréal/Conservatoire de musique du Québec, Canada
P5	39	m	CNSMD Lyon, Paris; Université de Montréal, Canada
P6	33	f	Université de Montréal, Canada; Conservatoire France
P7	23	m	Université de Montréal, Canada
P8	28	f	Winnipeg; McGill University, Canada; private lessons
P9	26	f	Université de Montréal, Canada, private lessons
P10	27	f	McGill University, Canada

Pianist	Style trained	Degree	Years training	Times per year
P1	Classical	Master	31 to 40	31 to 45
P2	Classical	Doctorate	21 to 30	0 to 15
P3	Classical	Bachelor	11 to 20	0 to 15
P4	Classical	Master	11 to 20	0 to 15
P5	Classical	Doctorate	31 to 40	0 to 15
P6	Classical	Doctorate	21 to 30	0 to 15
P7	Classical	Bachelor	11 to 20	0 to 15
P8	Classical, jazz	Bachelor	21 to 30	0 to 15
P9	Classical	Bachelor	11 to 20	0 to 15
P10	Classical	Master	11 to 20	0 to 15

D.4 Survey for pianists

1. Do you move a specific part of the body more than others while performing? If so, can you explain why?

2. Do you think you moved differently in order to perform the different levels of expression? For instance, were your movements affected by a particular condition?

3. For each excerpt, do you think you moved according to the structure of the piece you perform? If so, how? For instance, do you think that certain structural qualities in a piece help you convey the different expressions? Does the dynamic shape, the melodic and rhythmic forms, or the phrasing structure influenced your movements?

4. We asked you to play in different conditions: normal, deadpan, exaggerated and immobile. Would you say that playing in different expressive intentions has affected any particular expressive parameters? Is so, which one?

Table D.3 Pianists' answers to the survey

Pianist	**1. Do you move a specific part of the body more than others while performing? If so, can you explain why?**	**2. Do you think you moved differently in order to perform the different levels of expression? For instance, were your movements affected by a particular condition?**
P1	I was taught to use arm weight.	I aim at using various levels of arm weight depending on the type of expression. Specifically, upper body weight. So for the deadpan I use less weight and for the exaggerated more.
P2	Les bras. Parce que je n'ai pas le choix. Aussi pour que ça respire. J'essaie de créer une connexion entre mon corps et l'instrument. (C'est très difficile de se sentir bien connecté avec tous les dérangements de l'étude comme : piano électrique, juste une pédale, la hauteur du banc, la partition qui est loin, les capteurs etc.	J'ai tendance a rester plus figé quand je suis contraint de jouer sans expression. Quand je dois jouer plus expressif, je bouge un peu plus les bras et le corps au complet.
P3	No.	Yes. When I have to exaggerate I move more, whereas when I play deadpan I move much less.
P4	Probablement les coudes, puisqu'ils sont la principale connexion entre le reste du corps et les mains, dans le contexte du piano. Le dos peut bouger aussi en fonction du son necessaire et des mouvements requis pour la piece.	Je bougeais definitivement moins pour jouer "deadpan", probablement un peu plus pour ajouter de l'expression mais la difference dois etre moins frappante.
P5	Peut etre le bassin, mais sensation de bouger le corps de maniere globale.	Peut etre le bassin, mais sensation de bouger le corps de maniere globale.
P6	Les bras pour la detente corporelle et la "detente" sonore. Le tronc que je trouve en lien avec l'investissement emotionnel/dramatique.	Pour immobile: je ne bouge pas le tronc ni les coudes. Pour exagere: mouvement du tronc, ischions, coudes, bras. Pour deadpan: memes conditions que "immobile", sans bouger la tete.
P7	My head because it is the part of my body that is freer besides the arms. Even the body can only sway, but the head can really move.	Yes, because for me the movement is directly linked to the expression, and if I'm moving naturally then the expression just starts to happen without thinking.
P8	I think I move my arms and hands the most because they are the ones that are trying to directly shift position around the keyboard and my arm movement will shape phrasing.	I believe I moved differently. In the normal situation I did my "practiced movements" which I was thinking a lot about and actually felt more tense. When I did deadpan, I relaxed and did minimal movement. With exaggerated I just listened more to the sound which caused more movement but I felt more relaxed still. With restricted movement I found myself trying to do the same expression with the least movement necessary, which showed me places where potentially I was before doing excessive movement in effort to execute what I had practiced. I found this interesting to try to evaluate my movement in the normal condition. To find where I am doing excess movement, which is creating tension, and what I do expressively in deadpan and exaggerated. I based this on listening instead of focusing on movement.
P9	Le tronc car c'est le centre du corps et c'est de la que viennent les gestes.	Yes, the deadpan because expression comes from movement (in my case) and the immobile: it was hard to express music without natural movement
P10	My upper body helps with gravity to move around	Yes, when I move more I usually can feel more expressive

Pianist	3. For each excerpt, do you think you moved according to the structure of the piece you perform? If so, how? For instance, do you think that certain structural qualities in a piece help you convey the different expressions? Does the dynamic shape, the melodic and rhythmic forms, or the phrasing structure influenced your movements?	4. We asked you to play in different conditions: normal, deadpan, exaggerated and immobile. Would you say that playing in different expressive intentions has affected any particular expressive parameters? Is so, which one?
P1	The texture influences the technique so that when there are fast figurations, it is the use of finger work with less motion of the bigger parts of the body.	Deadpan affected the dynamics: it became more flat. Immobile affected the dynamic and fluidity.
P2	Dans le Medtner j'ai plus besoin de mes hanches pour les passages ayant un plus grand ambitus. La fantaisie-impromptu, la maniere dont elle est ecrite, me pousse a rester sur place et bouger moins.	Pour deadpan, j'avais tendance a reduire le tempo, faire moins de nuances, et garder un rythme plus stable, moins changeant et je reduisais le contraste entre les mains. Pour le "expressif", je variais plus le tempo, je m'efforcais a faire plus de nuances, plus de rubato, et je faisais plus de contraste entre les mains. Pour "immobile" , la psychologie de la chose me poussait a jouer deadpan, meme si ce n'etait pas mon intention. Comme si c'etait impossible de jouer avec une expression juste si je n'ai pas le droit de bouger.
P3	Yes, mainly the dynamic shape	Yes, in the immobile one. I found it hard to move as little as possible while maintaining the normal level of expressiveness. It was not easy to instantaneously think of ways to play as expressive as usual with less movements.
P4	Definitivement. Une longue ligne d'accords se traduit par un geste continue du corps, pour suivre la ligne, l'unifier et la rendre expressive. Parfois un allongement du dos pour eliminer une partie du transfert de poids lorsque je joue doux.	Je crois que ca affecte tous les parametres. Non seulement le tempo global, mais le rubato, le phrase, les nuances, etc.
P5	Pour le Medtner, l'interpretation et les gestes me semblent pouvoir etre plus fluctuants a cause de la progression en crescendo, qui peut etre plus ou moins retardee, et les variations de tempo indiquant la volonte d,une expression libre. cependant les gestes doivent etre calcules precisement pour la precision du jeu et des intentions. Dans l'impromptu le rubato du chant et le tempo modere permettent plus de liberte. La ballade demande une habilete et une souplesse dans un tempo assez allant, avec une stabilite du buste, rendant la version immobile plus facile que la version exageree.	Normal : plus facile car dans la zone habituelle Deappan : difficile, l'expression est contenue et le corps semble se fermer. la musique est vide Exaggerated : interressant car certains passages meritent d'aller chercher plus loin l'expression (degre d'intensite ou elargissement temporel). Par contre, d'autres passages sont perturbes au niveau de la realisation, de la precision et du controle du son. Immobile : entraine de la rigidite et des imprecisions dns les deplacements et le controle du son. mais permet de supprimer d'eventuels mouvements superflu dus a une agitation trop importante (ballade)
P6	Medtner: l'etendue des nuances, les accents (utilisation du mouvement vers l'avant du bras, ouverture du coude, degagement du tronc vers l'arriere au moment de l'attaque), et l'intensite dramatique generale rentre naturellement en ligne de compte dans le mouvement du corps. J'ai trouve plus difficile d'exagerer l'expression dans les passages tumultueux qui demandent deja naturellement un investissement corporel. Ballade: La polyrythmie entre les 2 mains ainsi que la rapidite des deplacements a la main gauche necessitent une certaine precision dans la realisation. J'ai trouve que le fait d'exagerer l'expression vient a l'encontre de cette precision et donc de l'expression.(par exemple: trop de variations de tempo nuisent a la precision rythmique). Impromptu: J'ai trouve que les variations expressives demandees etaient beaucoup plus faciles a rendre. Je pense que cela est du a l'ecriture assez uniforme (a deux voix) et a la simplicite rythmique.	Oui. Les variations de nuances, les variations de tempo.
P7	More than the structure, it's the phrases and the breathing of the piece that dictates what movements I make. Obviously a piece that is moving quicker and without large flowing gestures will restrict the kinds of movement I can do, whereas a piece that is slower with larger flowing gestures and phrases gives much more room to add movements. Dynamic shapes do make a difference, but all depending again on the speed and the type of phrase.	Immobile limited the dynamic contrasts simply because without a larger gesture it's impossible to produce more sound and also reduced what felt natural to do because without the movement it feels unnatural to be doing such expressive phrases etc. Exaggerated made the dynamic contrasts much more significant and I was taking much more time, whereas in Deadpan I was taking much less time and playing more literally.
P8	I think structure is key for comprehensive expression in a final product, though many people can be very expressive without understanding the structure, it just might not be as cohesive to the listener, like if someone reads a poem very expressively but doesn't really get the structure, it can still be interesting and have natural beautiful moments but the overall effect will likely not be as intended by the composer, or get the poetic goal across. I base my movements off of dynamic shape, melodic and rhythmic forms and phrase structure. This is something I am currently exploring and discovering for myself so I still feel uncomfortable with it in performance.	I believe the focus on listening in the different conditions in a way that wasn't the "right way" freed me to be more natural in whatever parameter it was rather than trying to get to my preconceived goal. So expressive intentions for deadpan made me see what phrasings were absolutely necessary or that I 'couldn't help' but do, and exaggerated allowed me to explore what seemed perhaps ridiculous in volume and tempo range, though probably it is actually not so exaggerated and has some things I would want to use in actual performance. Minimal movement had me just listen exactly to what I was producing so I could use minimal movement to get there.
P9	Yes (I tried). Basic technical movements required in some parts of the excerpt. For example the "improvised" part in Chopins ballade in the end of the phrase, or the quick notes at the end of Medtner. I tend to move more in a very "melodic" part such as chopin or when some parts require big jumps on the keyboard.	Yes, for example deadpan, I tried to reduce the dynamics to make it sound kind of "boring" and with less rythmic flexibility. Also the immobile performance, hard to play with natural expressions, because for me expression comes with movements.
P10	Yes when I did not feel the music I did not move as much as to play it without intonation is to use less of arm weight and gravity	Deadpan was hard to do as we are taught to play expressively and also immobile was hard to remember to be expressive as that gesture is usually used for contemporary music to create a certain atmosphere and sound

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