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Movement and touch in piano performance

Werner Goebl

Abstract Pianists achieve extreme levels of virtuosity on their instrument, requiring a combination of talent and decade-long continuous and deliberate practice, training, and experience. As with all musical behaviors, body movements in piano performance are goal-directed, aiming at producing intended sounds with utmost precision and accuracy in expressive parameters such as timing, dynamics, timbre, and articulation. Body movements in piano performance may also serve communicative purposes such as to express emotional states or to coordinate with co-performers. Pianists control the timing and velocities of the individual piano hammers by varying the forces applied to the piano key surfaces, as well as to the three pedals through their feet. The key forces are accomplished by coordinating the kinematic chain from their shoulders to the fingertips aligned with feet movements to manipulate the pedals. As kinematic properties such as finger velocity covary with performance parameters (tempo, dynamics, etc.), pianists have to stabilize several parameters of movement kinematics and musical expression simultaneously. The intrinsic way the fingers arrive at the piano key surface, referred to as piano touch (i.e., pressing versus striking a piano key), yield different tactile and other sensory percepts to the pianists themselves and the audiences alike, making this parameter an important one in accomplished piano performance.

Key words: Piano performance, Motion capture, Piano technique, Piano touch, Movement efficiency

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1 Introduction

Human movement in skilled piano performance is a remarkable example for the extreme capabilities that our bodies are able to achieve: professional pianists are able to produce highly regular sequences of up to about 16 tones per second such as in a Chopin Etude (Goebl and Palmer, 2013), they are able to precisely control hammer velocities of individual keystrokes between about 0.2 and 8 meters per second through variations of force on the key surface (Goebl et al, 2005), they easily achieve about 30 strictly increasing dynamics on one repeated tone (Tro, 2000), their fingertips experience impact peaks of more than 10 G when arriving at the piano key surface (Goebl and Palmer, 2008) – more than a fighter jet pilot would survive – and during a typical piano recital, they perform easily over 50,000 tones (Flossmann et al, 2010), each minutely timed and dynamically shaped to bring the musical image of the artist to perfection.

Human movement and music are closely intertwined, not only because music necessarily requires human body motion to be generated, but also because music induces the perception of movement in many different ways, such as with the impression of rising or falling of (the pitch of) a melody or a fast beat suggesting a fast musical movement able to drive humans to move and dance along with it (Phillips-Silver, 2009). This chapter focusses on the first, the highly skilled human movement that is required and precisely executed for and during playing the piano.

1.1 Purpose of movement in piano performance

Human movement in piano performance is primarily directed to produce sound imagined by the performing musician. Rather than being the goal of the artist (such as body movements in ballet dancing [REF: "Functional Movement Analysis in Dance"]), the movements serve another primary purpose – that is, the creation of sounds to be perceived by the audience (also referred to as "sound-producing gestures," Dahl et al, 2010, REF: "Body Movements in Music Performances – On the Example of Clarinet Players"). In this light, by studying human movement during music performance, we measure an important behavioral dimension that is located in the middle of the artistic chain from the musical idea, the musical work to its realization in actual sound (Bishop and Goebl, 2016). With increasing skill, pianists more successfully connect the auditory image of the sound to be played with the internal motor command that is required to produce it, so that they can just think of the sound and the required movement arises automatically (audio-motor integration, see e.g., Stewart et al, 2013). When practicing specific novel movements, pianist direct their attention to the particular movements ("internal focus"), but should shift their attentional focus to the sound afterwards to ensure seamless performance later on stage ("external focus," cf. Wulf and Mornell, 2008).

Beyond the goal of producing sound, human motion during piano performance may also serve other (in part unconscious) functions, such as communicating emotional aspects to the audience (REF: "Postural Movements of Violin Players"), coordinating with other musicians or facilitating the own performance such as tapping with the feet to help keeping the beat (Dahl et al, 2010, REF: "Movements, Timing and Precision of Drummers"). Viewing and listening to a piano performance, rather than just listening to it, has been shown to alter its perception considerably (Behne and Wöllner, 2011), to the degree that visual information alone is more predictive of identifying the winner of a piano competition than auditory information alone or auditory and visual information combined (Tsay, 2013).

1.2 Pianistic and scientific views on piano technique

Considering human movement in piano performance is central for pianists, piano educators and piano students themselves. They are primarily interested in how these movements can be trained and optimized through practice to establish an unlimited virtuoso technique on the instrument, while simultaneously minimizing the risk of injury. Pianists require a minimum of 10,000 hours or about 10 years of deliberate practice to achieve medium levels of expert performance skill; professional pianists exhibit even more (Krampe and Ericsson, 1996). Renowned pianists and piano educators have provided a wealth of writings describing different pedagogical and pianistic approaches to piano technique and how the piano ought to be played, ranging from pure verbal descriptions (Neuhaus, 1973) to using illustrative pictures or sequences of pictures to illustrate a particular movement (as in Gát, 1965, for an overview see Gerig, 1974).

Pianistic accounts of how to play the piano and to develop a proper keyboard technique started to appear in the 18th Century (Couperin, 1716; Bach, 1753) with reference to a range of keyboard instruments of that period. In the 19th century, when the piano developed to its modern form in tone compass and sound, pianism developed, as did theoretic writings about it. While one method of piano playing in the 19th century, the finger school, emphasized having every action executed by the fingers alone while other parts of the kinematic chain, hands, wrists, and arms were fixated and unmoving (e.g., advocated by pianists and teachers M. Clementi, J. B. Cramer, or N. Hummel, see Gerig, 1974; MacRitchie, 2015). Some proponents of the finger school even proposed mechanical practicing devices that helped to secure the wrist or the hand during piano playing (such as Johann Bernhard Logier's *Chiroplast*, cf. Rainbow, 1990). A radically opposing view became very popular in the late 19th century, when terms as "arm weight" and "relaxation" were the guiding vision of piano playing and "fixation" of any kind was to be avoided (e.g., Matthay, 1903; Breithaupt, 1905). Many pianists use such a terminology as metaphor for learning pianists to imagine the "correct" movements to be trained and executed on the piano. This terminology is often in conflict with what scientists actually find when analyzing piano technique experimentally. There is certainly no kind of piano technique that eliminates the muscular fixation of joints, be it only for short durations during a keystroke (Ortmann, 1929), despite the statements of some piano schools (e.g., Matthay, 1903).

On the other hand, scientists have been studying piano technique systematically already for almost a century. First systematic approaches to quantitatively monitor arm and finger movements during piano performance were provided by the piano professor Otto Ortmann (1929) in Baltimore and the scientists Nikolai Bernstein and Tatiana Popova in Moscow (see Bernstein and Popova, 1929 for the German publication or the edited English translation by Kay et al, 2003 of the same experiment publish in Russian), both challenged by several extreme statements of the arm weight school such as by Matthay (1903) or Breithaupt (1905).

Bernstein and Popova (1929) measured and analyzed repeated octave strikes of professional pianists with an optical 2D motion capture system able to record up to 600 frames per second (called the kymocyclographic method) and manipulated tempo and dynamics as independent variables. They concluded that dynamics only changed the quantity of the arm movement while tempo changed its entire construction. As they started out from an artistic perspective, they implied that demonstrating fast movement at a slow tempo as well as practicing fast movements at a slow pace would therefore not make sense (Kay et al, 2003). They also conclude that arm weight is physiologically only relevant at slow tempi.

Scientific investigation of piano technique has continued ever since and recording and analysis methods developed considerably, providing precise details and insights into its basic levels of control (see overviews by Furuya and Altenmüller, 2013; Metcalf et al, 2014; MacRitchie, 2015). However, both approaches to comprehending piano technique, the artistic and the scientific still have their fundamental difficulties in understanding each other's scope of insight (MacRitchie, 2015). This chapter attempts to reconcile some aspects of artistic and scientific approaches.

1.3 The scope of piano technique

The pianists use the piano keyboard and the three pedals as interfaces to generate their intended sounds on a piano (Goebl et al, 2005). By controlling the variations of force applied by their fingertips to the piano key surfaces, they vary the timing and the speed with which the hammers strike the strings. (There are certainly many other ways of producing sound on the piano keyboard, such as playing glissandi with the nail-side of the finger or playing note clusters with the fist or the entire lower arm, not to speak from the many possibilities to play directly on the strings or other parts inside the piano.) All possible timbral and dynamic variations on the piano are controlled by the exact timing and the speed of the (usually) 88 piano hammers in coordination with the dampers that regulate the duration of the sound by attenuating the string vibrations when released. A damper is either held up by a pressed piano key, the sostenuto (middle) pedal that extends the lifting of selected dampers, or – most commonly – by the right pedal that lifts all of them at once, creating a rich vibrant sound. This control space is only amended by the una-corda (left) pedal that shifts the piano action sideways to make the hammers strike only a subset of the one to three-stringed courses, causing a variation in timbre and a prolonged acoustical decay (Fletcher and Rossing, 1998).

The piano action interrupts the mechanical connection of the key and the hammer just before the hammer hits the strings (escapement) to allow the hammer to hit the strings and rebound from them freely (Goebl et al, 2014a). The pianist loses control over the hammer at this point of escapement, which is adjusted by piano technicians as close to the piano strings as possible. The final hammer velocity is thus the only physical parameter controlling the intensity and the sound of an isolated piano tone, independent of the intrinsic acceleration pattern of the key. The "single variable hypothesis" states that variations of what pianists call the "piano touch" are irrelevant for the sounding outcome; only variations in hammer speed are relevant for expressive piano performance (Bryan, 1913; White, 1930). This created a debate between pianists and scientists that spanned over a century (see discussion below), finally resolved toward the pianists' side (Goebl et al, 2014a; MacRitchie, 2015).

The effects of pianists' movements may be reduced to variations of force applied to the piano key surfaces in order to create variations in hammer velocities (White, 1930). Pianists make use of the entire kinematic chain of their arms, hands, and fingers that offer an unlimited number of possible movement combinations for a given task, usually referred to as the degree-of-freedom (DOF) problem (Bernstein, 1967). The scope of measurement techniques for assessing human movement in piano performance have to include kinematic (posture, motion), kinetic (dynamic and static forces and torques), and muscular (contraction and co-contraction of antagonist muscles) aspects, discussed in the following section.

2 State of the art

Measuring the movement effects inside the piano action has been easier and therefore more readily available for research than studying the human movements directly (for an overview on measurement techniques, see Goebl et al, 2008; Metcalf et al, 2014; Goebl et al, 2014b). Data derived from parts of the piano actions such as the hammer or key motion (as provided by MIDI-based instruments) or extracted from audio recordings have been used to study aspects of musical expression in piano performance by analyzing and modeling the performed realization itself (see e.g., Palmer, 1997; Gabrielsson, 2003; Widmer and Goebl, 2004, for reviews). In the following, we report approaches that make use of data of the movement effects or movement measurements, respectively.

2.1 Measuring movement effects on the piano action

Quantitative measurements of the key movements were attempted in the late 19th century by Binet and Courtier (1895) who used a graphical cylinder to record the air compression variations inside a rubber tube positioned under the piano keys. More systematic investigations were reported by Ortmann (1925) who mounted a tuning fork onto a piano key, the vibrating end of which wrote oscillating traces into a piece of smoked glass during a keystroke, capturing the specific velocity profiles of the key. With this setup, Ortmann (1925) was able to analyze different playing techniques through the velocity profile of the piano key (for more details and other approaches, see Goebl et al, 2008).

The first large-scale performance collections were made with recording systems that aimed to reproduce the pianist's performances as convincingly as possible through pneumatic reproducing systems such as systems by Welte or Ampico (Hagmann, 1984). Piano rolls have been used as source for systematic research into the musical expression of piano playing (Hagmann, 1984) as have specially developed devices such as the Iowa piano camera in the 1930s or Shaffer's photocell Bechstein in the 1980s (see Goebl et al, 2008). MIDI-based instruments such as digital pianos, hybrid pianos or reproducing pianos usually provide the exact information on the onset and offset timing and the dynamics in terms of a key or hammer velocity measure for each performed note (Goebl and Bresin, 2003). These data contain information on properties of the movements that generated those performance patterns. For example, Jabusch et al (2004) use such MIDI information of performances of a simple scale task as dependent variable to distinguish healthy pianists from those who suffer from focal dystonia (see also below).

Current reproducing pianos may also provide additional information on the key position history, an important component as it yields information on the type of touch used for a keystroke (i.e., the CEUS system by Bösendorfer Bernays and Traube, 2014; Goebl et al, 2014a). Similar data is provided by the custom-made gesture sensing keyboard that measures key position optically (McPherson and Kim, 2011). Other measurement devices track the location of finger-key contact on the key surface with a capacitive foil glued on it (McPherson, 2012) or provide information on finger forces applied to the key (force transducers underneath the keyboard, Parlitz et al, 1998 or onto the key surface, Kinoshita et al, 2007).

2.2 Measuring the pianist's body motion

The detailed measurement of the pianist's body during piano performance in a natural and minimally intrusive setting (that is a pianist performing on an acoustic grand piano with equipment that does not alter her or his performance considerably, but still offering kinematic and kinetic data on the entire movement chain from shoulder to fingertip) is still an open challenge (for overviews, see Dahl et al, 2010; Furuya and Altenmüller, 2013; Goebl et al, 2014b; Metcalf et al, 2014; MacRitchie, 2015).

There is still a trade-off between data detail, equipment complexity and measurement intrusion. For example, a Microsoft Kinect depth camera allows unobtrusive recording of unequipped pianists on an acoustic piano, but offers only coarse data on upper body and arm motion (e.g., Hadjakos, 2012). In contrast, marker-based optical motion capture at the level of finger movements requires minimizing occlusion problems, by employing digital pianos that allow free camera sight to the fingertips from the front of the pianist (that an acoustic piano prohibits due to its construction); however, using a digital piano reduces ecological validity (e.g., Tits et al, 2015).

The earliest motion capture approaches employed tracking devices specially developed for the purpose of piano movement analysis. Mechanical levers attached to the pianists' fingers or the arm were used to monitor the movement trajectories during a keystroke, to investigate specific kinematic properties of keystrokes executed with different types of touch (percussive versus non-percussive Ortmann, 1929). Ortmann also explored the use of light-bulbs, attached to wrist and fingers, that left a trace on a photo plate, to visualize a wide range of arm, hand, and finger movements (Ortmann, 1929). Using a similar basic principle, Bernstein and Popova (1929) also used active light-emitting markers mounted on the head, shoulder, elbow, and wrist to monitor the movement chain of a pianist performing repeated octave keystrokes at different dynamics and tempi. The recording apparatus, termed the "kymocyclographic method" was able to capture up to 600 frames per second, which is impressive even for today's standards (Kay et al, 2003).

The optical methods developed and employed by Bernstein and Ortmann were active marker-based optical systems similar to those used in today's piano movement research (e.g., Goebl and Palmer, 2009b). These systems have the advantage of delivering clean data and correct marker mappings, but are restricted in the number of markers and sampling rate and exhibit limitations in their size and cabling. The idea of mechanical motion tracking developed after Ortmann (1929) and more recent methods include for example electrogoniometers (devices mounted on joints, see Chung et al, 1992) and data gloves (a glove with open fingertips equipped with a number of joint angle sensors providing posture information from joint angles, Winges and Furuya, 2014).

Probably the most detailed motion data with a tolerable level of intrusion is obtained with passive optical marker-based motion capture system that use a variable number of infrared cameras to track the position of small reflective markers that may be mounted on the pianists body parts (for an overview, see Goebl et al, 2014b). The number of markers is not limited and sampling rates go up to about 500 frames per second. There have been studies measuring pianists' body motion at finger level (e.g., Ferrario et al, 2007; Tits et al, 2015; Dalla Bella and Palmer, 2011; Goebl and Palmer, 2013). But particularly at tracking pianists' finger movements, optical motion capture has to deal with marker occlusion at thumb-under maneuvers or when curled fingers render fingertips invisible. To overcome the latter, cameras are placed such that they also monitor the movements from the front-side of the keyboard, which is only possible for digital pianos. The use of acoustic pianos is still an open challenge, as the key lid makes the front-side view impossible and fingertip occlusion is omnipresent.

In passive optical systems, marker tracking and identification may present a post-processing problem. A recent study formulated a proportional relationship between minimal required frame rate, the smallest marker distance and the largest marker speed that a motion capture algorithm is able to track (Song and Godøy, 2016). For tracking pianist's fingers, typical marker distances of down to 20 mm and finger speeds of 2 m/s require a motion sampling rate of larger than 244 fps.

A solution to fingertip marker occlusion at optical systems are magnetic tracking systems (such as used by Rahman et al, 2011, who used 32 magnetic 6DOF sensors on both hands of a pianist to reconstruct hand and finger movements). This setup also works on an acoustic piano, but pianists are limited in their performance by the many cabled receivers and transmitters attached to their hands and fingers.

Inertial sensors (normally containing accelerometers and gyroscopes) have also been used to track aspects of pianists body motion. Hadjakos et al (2008) mounted cabled 6DOF inertial sensors on pianists wrists to visualize the motion of the lower arms together with a piano roll display. Current commercial systems link real-time data of multiple inertial sensors to reconstruct full-body motion; however, finger data has yet to be added.

Minimally intrusive solutions with maximal ecological validity are video-based with either some graphical markers painted on the hand (MacRitchie and Bailey, 2013) or even completely without markers, e.g., by using depth image data from a Microsoft Kinect (Hadjakos, 2012). MacRitchie and Bailey (2013) used a single camera image placed above the piano keyboard to track the motion of the 10 fingers of a pianist, even estimating the height dimension from marker distances. Combined with finger-keyboard interaction data provided from additional devices, the data quality was enhanced (MacRitchie and McPherson, 2015). Hadjakos (2012) tracked head, shoulder, arm, and hand movements with a Microsoft Kinect placed above the piano keyboard. The tracking accuracy and precision was in the range of 3–5 cm, so possible applications may be in visualization of large-scale body movements, but not any more detailed analysis. There are attempts of multi-camera markerless motion capture to study the biomechanics of full bodies, such as by Corazza et al (2006), but they have not been adapted for precise finger tracking, required for the study of piano performance.

3 Biomechanical and pianistic attributes of movement

The artistic control space of a piano is spanned by the wide range of possible force variations applied to the surfaces of the piano keys and the three pedals (also referred to as "endpoint redundancy," Furuya and Altenmüller, 2013). Pianists generate the force variations at the piano keys predominantly by controlling the joint movement and torques of the kinematic chain of the upper limbs, from the shoulder, elbow, wrist to the finger joints. The infinite possibilities of organizing the degrees of freedom of this kinematic chain are described by the "kinematic redundancy" (joint movement), "kinetic redundancy" (joint torques, developing from muscular, gravitational, inter-segmental and reaction forces), and the "muscular redundancy" (e.g., the balance of agonist and antagonist muscles, Furuya and Altenmüller, 2013).

An important aspect in piano technique is the movement independence of the fingers from each other. While non-musicians usually display larger finger enslaving between the middle and the ring finger than for the index and the little finger, which is in part due to biomechanical coupling (Häger-Ross and Schieber, 2000; Zatsiorsky et al, 2000), pianists exhibit similar levels of finger independence across all fingers (Furuya et al, 2011a), suggesting that finger independence can be achieved through long-term training. Furthermore, a timed finger tapping study involving all possible finger combinations showed that finger motion was modulated by biomechanical constraints, but this did not influence the timing accuracy, suggesting that cognitive control surmounts biomechanical restrictions in skilled performance (Loehr and Palmer, 2007).

Piano playing is more than the successive execution of individual movements; often individual movements are overlapping or require anticipatory movements to secure seamless transition of successive events. This effect is termed "coarticulation" in speech research (Fowler and Saltzman, 1993), but has been shown in finger spelling (Jerde et al, 2003) and piano playing (Engel et al, 1997; Goebl and Palmer, 2006). Pianists change their movement trajectories up to 500 ms before a leap or a thumb-under movement to master the horizontal relocation in comparison to a baseline condition (Engel et al, 1997). Practicing anticipatory movements is explicitly recommended by renowned piano educators to develop fast and difficult passages with horizontal relocation requirements (in the case of the left hand in Chopin's Prélude Op. 28 No. 3, see Neuhaus, 1973).

3.1 Piano touch

> "There may be players for whom touch and assault are synonymous. (In German, we find the deplorable word *Anschlag*, to strike). The pianist can indeed assault the piano and, for good measure, the composer and the public. To languages that propose a more loving vocabulary, like touch and *touché*, we owe a debt of gratitude." (Brendel, 2013, p. 100, emphasis in original)

The way pianists manipulate the key surfaces of the piano keys with their fingers is referred to as piano touch and has been a vibrant topic of debate among pianists, piano educators, piano students, and piano lovers since the first pianos were introduced (Goebl et al, 2014a; MacRitchie, 2015).

In the early 20th century, a physicist's view on piano tone and dynamics began to spread that supported the so-called "single variable hypothesis" (Bryan, 1913). This hypothesis refers to the fundamental mechanics of the piano action in which the hammer travels freely to the strings after the jack has been thrown aside by contact with the escapement dolly, causing the pianist to lose contact with and control over the hammer (Fletcher and Rossing, 1998, p. 354). The single variable hypothesis assumes that only the speed with which the piano hammer hits the strings determines the loudness and the timbre of an isolated piano tone. Therefore, it does not matter whether it is the well-trained finger of an exquisite piano virtuoso or a volume of Beethoven sonatas slipping down from the note stand that is producing a given tone. Only when the final hammer velocities are the same will the two tones be indistinguishable even for the most refined ear. This view has been the technical basis for modern reproducing pianos that measure and reproduce the final hammer velocities of each single piano hammer irrespective of the specific touch and succeed to create convincing reproduction results (Goebl and Bresin, 2003).

However, pianists have a more complex view of the way they interact with the piano action in an artistic manner (for an overview, see MacRitchie, 2015). To describe different ways of touching a piano key, pianists and scholars use antagonistic terms such as *percussive* versus *non-percussive* (Ortmann, 1929), *staccato* versus *legato* (Askenfelt and Jansson, 1990), or *struck* versus *pressed* (Goebl et al, 2005; Kinoshita et al, 2007). The former denotes a keystroke in which the fingertip arrives at the key surface with a certain speed, accelerating the key in a sudden, percussive manner, while the latter describes a fingertip already resting at the key surface and pressing it down by accelerating it gradually.

These opposite ways of accelerating a piano key may generate identical final hammer velocities, but they still entail typical kinematic, mechanical, acoustical, and perceptual differences: struck keystroke movements exhibit larger shoulder and finger flexion velocities in repeated arm strikes than pressed ones (Furuya et al, 2010), struck keystrokes require less time to generate a sound than pressed ones for piano tones that are equally loud (Goebl et al, 2005), and struck keystrokes have a characteristic finger-key "noise" component in the radiated sound that is absent in pressed tones (Askenfelt and Jansson, 1990). This finger-key sound enables listeners to identify the particular touch movement that generated an individual piano sound (Goebl et al, 2014a).

Today, piano touch is regarded a multi-modal phenomenon including auditory, visual, tactile, and proprioceptive components and therefore concerning all aspects of piano technique. In this light, the century-old single variable hypothesis of hammer velocity is outdated in current approaches of studying piano performance (MacRitchie, 2015).

3.2 Effects of intended tempo and dynamics on movement

Expressive piano performance requires pianists not only to accurately time their many keystrokes, but to shape their dynamics at the same time by controlling the acceleration patterns of the keys (see above). These parameters interact with one another, so a louder tone requires a faster striking movement, which needs to be initiated later than does the striking movement for a softer tone to create a sounding tone at a given time instant. The human motor system must control these interacting parameters simultaneously.

To create louder octave strikes, pianists reorganize their movements in a particular way: experts increase their shoulder deceleration to increase elbow rotation, while beginners use more muscular load at the elbow to come to the same goal (Furuya and Kinoshita, 2008; Furuya and Altenmüller, 2013). Experts additionally reduce the elbow flexor activity working against gravity, thus utilizing “arm weight” to produce a keystroke, while beginners use agonist elbow muscles for the same goal (Furuya et al, 2009).

While fundamental movement kinematics such as joint contributions to the final fingertip movement (Goebl and Palmer, 2013) or movement covariation between striking and non-striking fingers (Furuya and Soechting, 2012) have been shown to remain stable across different performance tempi, several other parameters do change. With a faster performance tempo, pianists raise their finger higher above the keyboard (Dalla Bella and Palmer, 2011), contradicting common recommendations from pedagogues to keep the fingers as close as possible to the key surface when playing very fast passages. Similarly, the instants of finger movement initiation (maximum finger height) and of movement goal (tone onset) move closer together in time with faster tempi (Goebl and Palmer, 2009a), but not as much as the inter-onset interval, the time interval between successive tone onsets, decreases. Keystroke finger movements that are successive at slow tempi (one is accomplished before the next is initiated) do overlap largely at very fast tempi, so pianists need to modify the temporal organization of their finger movements at different tempi (Goebl and Palmer, 2009a).

The occurrence of the type of touch is also modulated by the performance parameters tempo (faster tempi have larger proportions of struck keystrokes, Goebl and Palmer, 2008) and dynamics (soft tones tend to be produced by pressed touches, while loud by struck touches, Goebl et al, 2005). At slow tempi, pianists have control over the choice of touch, while at fast tempi only struck touches are feasible (Goebl and Palmer, 2008). Different ways of touching the keys induce different tactile sensations in the performer that might be used to stabilize timing control in performing isochronous sequences (Goebl and Palmer, 2008).

3.3 Role of expertise

A practical and effective experimental paradigm to understand movement organization in skilled piano performance is to compare performances of highly trained expert pianists to those of novice pianists (Furuya and Altenmüller, 2013). Movement organization in highly skilled pianists differs fundamentally from those of beginners. Experts strive to achieve physiological efficiency by reducing muscular load and making more use of proximal joints and gravitational, inter-segmental and reaction forces than beginners (Furuya and Altenmüller, 2013).

In a forced repetition task that required pianists and novices to keep up playing octaves loudly (*forte*) at a rate of 4 Hz over the period of half an hour (thus producing over 7,000 keystrokes), only experts were successfully accomplishing this

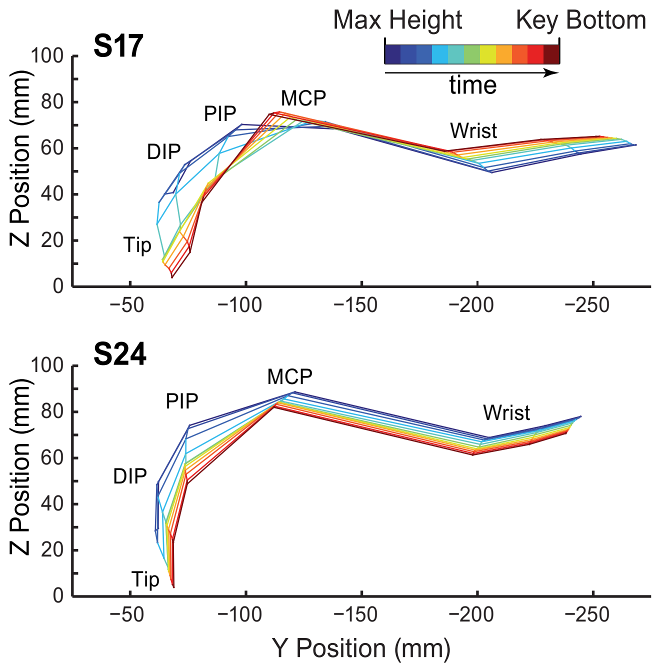

Fig. 1 Examples of finger keystrokes on the piano with contrasting movement efficiency. Stick figures of the joints of the middle finger and the wrist of two pianists, seen from a side perspective. The time from the maximum finger height above the keyboard as the start of a finger striking movement through to the key-bottom impact as its end are color-coded from blue to red. Pianist S24 showed higher efficiency values than S17. Figure taken from Goebl and Palmer (2013).

task suggesting that the specialized movement organization of experts enables them to avoid muscular fatigue (Furuya and Kinoshita, 2008). Similar results have been confirmed for a tremolo task (quick and repeated alternation of two tones played with thumb and little finger), in which experts used more proximal muscles and less finger flexion than amateurs (Furuya et al, 2011b). Experts applied less force for a shorter duration to the piano keys than beginners to keep a piano key pressed down after a keystroke (Parlitz et al, 1998).

As physiological movement efficiency becomes more important for the performance of very fast passages, pianists with more efficient keystroke finger movements achieve faster maximum tempi than others. A kinematic measure of keystroke efficiency confirmed this experimentally with a dozen pianists performing isochronous finger exercises from medium fast to very fast tempi. The pianist achieving the fastest possible tempo condition also showed highest keystroke efficiency values, while those with lower keystroke efficiency only reached medium fast maximum tempi (Goebl and Palmer, 2013). To illustrate, Figure 1 shows stick figures of example keystrokes of two contrasting pianists. The upper graph represents a finger keystroke with a distal inter-phalangeal joint (DIP) clearly breaking in and a metacarpal phalangeal joint (MCP) flexing excessively to compensate this breaking-in of the DIP joint, resulting in a less efficient keystroke movement. The lower graph shows a keystroke from one of the fastest pianists with high kinematic efficiency. The majority of endpoint motion is generated in the MCP joint, while the other finger joints barely move. This latter keystroke exhibits significantly larger efficiency values than the former (Goebl and Palmer, 2013).

3.4 Movement disorders in piano performance

The high demands of the concert podium and the resulting competition among pianists require them to undertake enormous practice efforts, which may often result in overuse syndromes or long-lasting injuries, also referred to as playing-related musculoskeletal disorders (Metcalf et al, 2014, REF: “Motion Analysis as Preventive and Rehabilitative Measures in Dance Medicine”). Among the most frequent pathologies in professional pianists are tendinitis (tenosynovitis, Sakai, 1992), the tennis elbow (lateral epicondylitis, Metcalf et al, 2014) and, most dramatically, focal dystonia (Konczak and Abbruzzese, 2013).

Focal dystonia is a neurological motor disorder that affects specific regions of the body (such as the right hand of the pianist) and is typically reflected in involuntary movement impairments in task-specific actions that are highly trained (for overviews, see Altenmüller et al, 2012; Konczak and Abbruzzese, 2013). The prevalence of focal dystonia in professional musicians is roughly one percent and affects considerably more males than females (Altenmüller et al, 2012). Focal dystonia is associated with a genetic predisposition (Altenmüller et al, 2012), depression, sleep problems, a decreased precision of tactile and proprioceptive perception (Konczak and Abbruzzese, 2013), as well as behavioral triggering factors such as practicing repetitive passages over prolonged time spans (Furuya et al, 2015). Cortical maladaptations in the somatosensory cortex, the basal ganglia and the cerebellum have been documented for focal dystonia patients (Furuya et al, 2015).

In pianists, focal dystonia causes involuntary contraction of antagonist muscles during the execution of well-trained movement sequences, such as playing scales or chords. Pianists suffering focal dystonia show smaller finger flexion maxima, lower between-finger independence and larger timing variability than healthy controls, according to a recent sensor-glove study (Furuya et al, 2015), documenting clearly the deterioration in fine motor control in focal dystonia patients.

4 Future directions

Despite a long history of scientific investigation of human movement in piano performance, research in this direction is still to develop. Current restrictions in capturing the detailed body motion during piano performance such as fingertip occlusion or measurement intrusion need to be overcome with new technologies and analysis approaches. Systems are required that are more reliable and less intrusive (like optical marker-less motion capture), that use only a set of high-speed cameras, combined with refined and complex computer vision algorithms able to reconstruct the skeletal movements at the level of individual finger, hand, and arm phalanges.

The opposition to integrate scientific findings into the daily musical experience of pianists is still pronounced, not only because of technical hurdles that restrict the use of motion capture technology to the professional laboratory rather than the stage of the practice studio. Initiatives in the future should try to fill the gap between artistic and scientific investigation of the same phenomenon by finding a mutual language and accepting the fundamental differences in approach and goal (MacRitchie, 2015). It would be desirable to convince pianists to trust and apply quantitative methods in optimizing their playing technique (Wulf and Mornell, 2008) just as expert athletes in many sport disciplines do on a regular basis.

5 Cross-References (to other chapters of the handbook)

- Body Movements in Music Performances – On the Example of Clarinet Players doi:10.1007/978-3-319-30808-1_107-1
- Observing and Learning Complex Actions: On the Example of Guitar Playing doi:10.1007/978-3-319-30808-1_191-1
- Investigating Aspects of Movement in Violin Performance doi:10.1007/978-3-319-30808-1_108-1
- Movements, Timing and Precision of Drummers doi:10.1007/978-3-319-30808-1_110-1

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