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The art and science behind piano touch: A review connecting multi-disciplinary literature

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Abstract
The touch used to play the piano, representing aspects of body posture, hand posture, movement, speed, force and pressure on the key, has been addressed over the centuries by pedagogues, famous pianists and composers. Piano touch not only underpins basic technique in piano playing, but is also the route through which pianists can communicate their expressive intentions. This review pulls together literature concerning touch from piano pedagogy, engineering, performance analysis and biomechanics. Studies have advanced understanding in the actions behind a typical keypress motion, the influence of training by examining differences between novice and expert pianists, and the various joint contributions that discern a struck versus a pressed touch. Although individual differences are widely identified, the influence of hand anthropometry, choice of technique and difference in training between experts remains understudied. A trade-off between accuracy and ecological validity is also identified in the use of current measurement systems: to encourage wider participation and incorporation into instrumental lessons, there is a need for the development of un-intrusive measurement systems that can be used outside the laboratory environment without restrictions concerning the instrument. Implications include furthering understanding across the arts and sciences and aiding teachers and students looking to minimise the risk of injury.

Keywords
touch, piano, pedagogy, biomechanics, musical performance, review, movement analysis

Introduction

Piano touch may be considered as a finger-key abstraction of movements carried out across the upper body, embodying the pianist's intentions for the sound. It has been pondered by eminent pianists, described by numerous pedagogues and investigated empirically from several scientific angles (see Gerig, 2007 for a review of pedagogical methods and Furuya & Altenmüller, 2013 for a review of biomechanical literature). However, despite these numerous definitions and descriptions, and the development of high-precision measurement techniques such as 3D

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motion capture, accelerometers and force transducers, we understand little regarding the range of motions underpinning any one specific touch technique.

Piano touch describes the interaction between pianists and their instrument, with tactile and aural feedback providing a number of benefits in terms of timing and sound production. Touch is also a term used to refer to a certain quality of the pianist's technique: masters of the instrument are often acknowledged as having a "beautiful touch". Touch is defined not only as a set of physical descriptors to depress the keys but also as a tool for pianists to mediate between the expressive intentions and the required actions at the point of finger-key contact. Although touch technique is recognised as being the mechanism used by pianists to control minute differences in the timing and velocity of each keypress, the relationship between gesture and sound is not always clear, particularly for students learning the instrument. Furthermore, this lack of knowledge of the physical keypress motions used across various contexts, compositional or expressive, and influenced by different hand anthropometry (hand span, finger length etc.) or choice of techniques, hampers attempts at minimising the risk of injury in instrumental tuition.

This review will draw upon pedagogical approaches and definitions of touch listed in piano pedagogy texts, and provide an analysis of the measurement techniques developed to study this question of what piano touch is and how it can be measured. The results of research conducted in performance analysis and biomechanical science using these measurement techniques will then be detailed, identifying areas for further study that may help to close the gap between experimental study and instrumental instruction. A major issue is in reconciling the results of quantitative studies, and the measurement devices used to quantitatively record aspects of performance, with pedagogical theories that are largely experiential and individual, having been refined through observations made throughout a teacher/performer's career. There is often a fundamental difference of approach, with artistic approaches focusing on the phenomenology and individual performance traits and scientific approaches focusing more on the generalisable characteristics that pervade pianists as a group. However, this review will demonstrate that there are common concepts and definitions of touch that permeate across the many pedagogical methods today, and that these can be used to motivate objective studies. Equally, it will demonstrate that results of scientific explorations often elucidate important biomechanical differences that arise from training, whilst also highlighting the individual differences that inevitably occur in a keypress, and that these can be used to inform students and teachers, furthering their understanding of their motions at the piano.

Definitions and Pedagogical Background

Historical Development of Piano Technique

Although references to different types of touch in keyboard technique are found regarding instruments such as the harpsichord and clavichord (see Couperin, 1716 for example), with the introduction of the pianoforte, and the potential for large dynamic differentiation between single keypresses, pedagogues and composers throughout the 18th and 19th centuries wrote in great detail concerning different aspects of technique regarding hand posture, movement and fingering choices. Although reference is often made to the French, German and Russian national schools of playing, which characterize many differences in interpretation style (Lourenço, 2010), it is difficult to attribute exact definitions of touch technique to any one, as the schools did not develop in isolation and are heavily influenced by each other (Bermann, 2000). The development of touch technique can be categorized into two distinct approaches:

the finger school, and the arm-weight school. The finger school including pedagogues such as Clementi (1803), Cramer (1812) and Hummel (1828), proposed that all action should come from the fingers, and promoted a separation between the segments of the arm and the hand: arm motions should be kept to an absolute minimum. Focus was on the equal sound that could be achieved across all fingers. Czerny (1839), although considered part of the finger-school, hints at later techniques, introducing the concept of 'weight' and advising the use of arm movements, albeit in a reduced form compared to later methods. References to 'arm weight' appeared in the second half of the 19th century, with Kullak (1893) advocating the use of the arm to enable more intense expression, although it was with texts such as those by Breithaupt (1909) and Matthay (1903; 1947) that the arm-weight school formed its opposing view, advising a more embodied approach to touch technique and the use of postures which followed the natural curves of the hand. However, pianists were often confused by the ambiguous use of the words 'arm-weight' and 'relaxation', wrongly assuming that the latter referred to complete relaxation of the joints. Other methods attempted to draw the advantages from each school of technique. For example, Levinskaya (1930) amalgamated these two schools of technique in order to preserve the precise control of all movements of the fingers whilst utilizing the natural falling and swinging of the arm with a term defined as 'controlled weight'. Differences between the two main technique schools could be related to the development in piano instrument building: delicate finger touch would be necessary to control the minute changes on an early piano, whereas a larger force of keypress was required to achieve the range of dynamics possible with the newer pianos. However, aspects of these two groups are still applied in piano pedagogy today (see Gerig, 2007; Gustafson, 2007; Wheatley-Brown, 2011 for full reviews of pedagogical methods in this time period).

A number of these pedagogues often devised technical exercises in order to help pianists master the required aspects of a particular passage so that they could repeat it during a performance of a complex piece (Gellrich & Parncutt, 1998). Exercises designed by those in the finger school encouraged equal strength and independence of the fingers (such as those by Bach and Czerny) whereas others, such as Chopin, advocated what he saw as the specific properties of each finger, maintaining that fingering choice would have an audible expressive effect (Eigeldinger, 1986). Cortot (1928) highlighted the role of the wrist in guiding finger movements, Kullak going a step further to recommend different fingerings based on the magnitude of pianists' wrist movements. Kullak's fingering system was based not on a set of composed exercises, but on his quasi-scientific exploration on the active muscles behind each kind of touch (Gellrich & Parncutt, 1998; Kullak, 1893).

The pedagogical methods described so far are based largely on subjective experience. Pianist Otto Ortmann (1925; 1929), informed by the fields of physiology and engineering, conducted one of the first objective examinations of piano technique, using devices such as a mechanical arm to monitor tone production, and a pantograph to record arm movements. Through a series of studies he related timbral descriptors to the acoustical properties of the piano, namely through changes in key velocity. He summarised that a performer only had control over the speed with which the key is pressed. His chapter on touch defines two types: percussive, where the finger either starts from a height above the key, or non-percussive, where the finger begins from rest on the surface of the key. Ortmann also acknowledged that the fluidity of the pianist's movements could influence how the notes were physically played. For example, fluid movements would produce legato sounds of similar loudness whilst jerky movements may cause some notes to be suddenly louder than their preceding counterparts, upsetting the overall performance. Schultz (1936) built on Ortmann's work, examining finger co-ordination, combining small muscle movements of the fingers with larger muscle movements of the arm. He found that the ability to control tone and volume within a keypress could not be maintained if the pianist was to understand 'relaxation' as complete relaxation of all joints of the arm.

Despite this wealth of literature concerning piano technique and finger usage, many modern pianists remain unaware of the fingering strategies they themselves use, and have only a limited understanding of the physics and physiology behind their motions in performance (Parncutt, 2007). The majority of pedagogical theories benefit from being underpinned by the subjective experience of the performer/teacher, but simultaneously lack the objective evaluation that allow pianists to discover the mechanisms behind the act of touch. Although this lack of knowledge does not preclude an aspiring student from becoming an eminent musician, there may be many benefits of a deeper understanding of the motions behind their gestures at the piano: from being able to better realize their expressive intentions to knowing the consequences of certain movements that through time could lead to injury (see Brown, 2000 for an example that uses biomechanical knowledge to dispel certain myths surrounding piano technique).

Current definitions and piano touch methods

Current pedagogical methods often adopt numerous aspects of older techniques, but are also highly individualized, crafted through years of experience (see for example methods by Seymour Fink and Seymour Bernstein). Kochevitsky (1967) turned attention to the role of the central nervous system, suggesting that a clear and precise 'musical image' of the sound would ultimately lead to the best physical movement for the realisation of that goal. Other methods such as those by Dorothy Taubman and Barbara Lister-Sink focus on injury prevention (see Wheatley-Brown, 2011 for a comparison of various techniques). Changes in touch are further manipulated by the performer based on the expressive intention and musical context. Bermann, 2000, p.26 provides such an example where the technique required for playing forte chordal passages in Rachmaninov's Second Piano Concerto may not be appropriate for chordal passages in Beethoven's Sonata in C Major Op.2, No.3. Problems arise in comparing these many pedagogical methods as they vary widely in terminology and definitions of concepts such as tension (Wheatley-Brown, Comeau & Russell, 2014), as well as varying opinions on the aspects of technique that determine touch (MacRitchie & Zicari, 2012). A large part of this confusion is spurred by general misunderstandings of biomechanics made by piano professors in their attempts to incorporate a knowledge of arm kinematics and the appropriate use of the muscles into their techniques (Wheatley-Brown, 2011).

Difficulties are also found in reconciling definitions of piano touch from different disciplines. Bermann (2000) provides an example describing six aspects of touch: weight (how much weight is applied to the key); mass (how much of the body is involved in the keypress); speed (of keypress); perception of depth (comparison of deep or shallow touch); shape of the fingers (including curvature, amount and location of contact on the pad or fingertip). This final aspect is addressed by Parncutt and Troup (2002) in terms of producing optimally efficient movements: the curvature of the fingers allows stronger forces at the fingertip. A definition from the scientific domain, drawing on measurements of physical parameters (key-angle in this case) from pilot studies with professional pianists is provided by McPherson and Kim (2011). They identify five dimensions of key motion: velocity (speed of key), percussiveness (analogous to Ortmann's definitions of percussive vs non-percussive), rigidity (finger joints loose or rigid on finger-key contact), weight (force into the key-bed immediately after a keypress) and depth (whether the key reaches the key bed or stops beforehand). An obvious contrast between the two examples is that Bermann's description is from the perspective of the performer, their perception and tactile experience of the finger action involved, whilst McPherson and Kim's focus on the physical attributes of the produced action. This is exemplified in the aspect of 'weight', which is used in both descriptions but defined in entirely different terms. Parncutt (2013) succinctly describes the gap between definitions found in the sciences and arts, particularly concerning timbre, a property of sound that pianists aim to manipulate with their touch. Since the two disciplines do not share a definition of timbre, both fail to reconcile the physical parameters with the outcome, as difficulty exists in separating the physical properties from the subjective multisensory experiences of performers and listeners. Although crafting unambiguous definitions from pedagogical literature (from which scientific investigation can begin) may seem impossible, Bermann (2000) suggests we can generalize to a few distinct properties that concern a large number of piano techniques: independence of the fingers, arm rotations, and the use of weighting in the arms. We add to this list the distinction between percussive and non-percussive touches (often referred to as struck and pressed touches), although struck touches can encompass a range of initial velocities of the finger at the time of finger-key contact. The studies detailed in the following sections attempt to address these generalisations, aided by the design and use of various measurement devices.

Measurement Techniques for Touch in Piano Performance

Existing experimental knowledge concerning piano touch is framed by the devices developed to measure its physical parameters. Progressing from research in the past few decades where MIDI has been the tool of choice in order to study aspects of expressive timing, a number of devices have been developed in order to accurately measure the complex movements of the hands during piano performance (for a complete review, see Metcalf, Irvine, Sims, Wang, Su & Norris, 2014). The following recent literature encompasses hand/key movement measurement methods that have either been designed specifically for a musical performance context, or demonstrate the use of a device designed for a wide number of applications in this particular context. The focus of these methods range from the hands themselves, to actions of the keyboard that can be measured as results of particular movements. Systems can be split into either passive (paint or reflective markers used, or markerless systems) or active (devices which require power whether that be by battery or via cable to a power supply). Motion capture is a common type of passive system used to examine the upper body or hand/finger movement of the performer: examples of these are depth camera tracking using the Kinect system (Hadjakos, 2012); image motion capture with paint markers (MacRitchie & Bailey, 2013); infrared motion capture using reflective markers attached to the skin or body (Dalla Bella & Palmer, 2006, 2011; Ferrario, Macri, Biffi, Pollice & Sforza, 2007; Furuya, Goda, Katayose, Miwa & Nagata, 2011; Goebl & Palmer, 2008, 2013; Sakai, Liu, Su, Bishop & An, 2006). Active devices can be categorised into two groups: the first which are generally attached to the performer (LED position sensors - Furuya & Kinoshita, 2007; accelerometers - Hadjakos, Aitenbichler & Mühlhäuser, 2008; Rahman, Mitobe, Suzuki, Takano & Yoshimura, 2011; Grosshauser, Tessendorf, Tröster, Hildebrandt & Candia, 2012; data glove - Furuya, Flanders & Soechting, 2011; Furuya & Soechting, 2012; electrogonimoters - Chung, Ryu, Ohnishi, Rowen & Headrich, 1992), the second which are attached to, or form part of, the instrument in order to measure the tangible results of such touch techniques (key-angle - McPherson & Kim, 2011; Bernays & Traube, 2012; location of finger-key contact - Moog & Rhea, 1990; McPherson, 2012; force transducers - Parlitz, Peschel & Altenmüller, 1998; Kinoshita, Furuya, Aoki & Altenmüller, 2007; force and torque sensors - Grosshauser, Tessendorf, Tröster, Hildebrandt & Candia, 2012).

The disadvantage that the human motion analysis systems share is a trade-off between accuracy and ecological validity of the measurement. With the passive motion capture systems, specifically infrared systems, an acoustic piano may not be used due to the noise the reflections of the surface often introduce into the system. Digital pianos also have the advantage of built-in MIDI input and output, so the majority of studies use these to collect measurements of timing and key velocity. Although studies using digital pianos give a close approximation to the measurements required of a general keypress movement, we cannot be certain of the effects of the different characteristics of pianos in terms of the tactile resistance experienced from pressing a key, through to the properties of the sound produced dictated by the finger-key-hammer action. All of these properties can vary substantially across different sizes and makes of acoustic pianos. Image motion capture systems have an advantage in this respect as they can be used in most performance environments, although the occlusion within a thumb-under movement or even the curving of the fingers on the piano can results in missing marker traces. Active devices perhaps provide the most accurate measurements in this sense, although the limitations within the context of musical performance are obvious: attaching devices of any weight or that generate any obstruction to the performer's natural movements could compromise accurate measurements of the performance act. The design of various devices measuring key effects on regular acoustic pianos is therefore attractive, as they provide a closer approximation to the effects expected in performing environments. However, in piano touch, these measurements only provide data on the result of the gesture, and not the posture, movements and coordination between the fingers of the hand used to generate that result. In this sense, we often find that a combination of measurement systems is used in research studies (for example, Furuya, Aoki, Nakahara & Kinoshita, 2012 use both LED markers for motion capture in conjunction with a force transducer on the key).

Cost and accessibility remain barriers to wider participation, both in experimental studies, and in using measurements to inform instrumental lessons: a large number of these systems (both for human motion analysis and key movement analysis) are expensive and/or difficult to use without extensive training. The implications of this are that these systems are often restricted to use in laboratory environments and cannot be distributed and used on a wider scale. Broader development of inexpensive, user-friendly systems that allow easy measurement and display of hand/body posture and movement will ultimately aid students in visualising the intended gesture and teachers in minimising postures or movements that could lead to injury.

The results from these current measurement systems provide information regarding the motions of the arm joints in a typical keypress, leaving aside the particulars of the instrument. This information is vital in piecing together the actions required for basic piano technique. The following section reviews the literature regarding the biomechanical analyses of keypresses for various compositional and expressive requirements.

The Keypress - acoustic and biomechanical studies

The redundant degrees of freedom within the arm and finger joints used to produce a keypress means that there are infinite possibilities for the movements needed to produce this action (Bernstein, 1967). This is exemplified by the large variability that can occur in hand movement during a variety of tasks such as grasping an object, pointing to a target, or pressing a key. The majority of biomechanical studies of pianistic keypresses are reviewed in Furuya and Altenmüller (2013), which summarises the reorganisation in movements that can develop with increasing skill in piano performance; for example, Furuya, Nakamura and Nagata (2014a; 2014b) demonstrated how finger motion is optimized through repeated practice of technical exercises by novice pianists. As pianists increased their skill, results showed the decrease of covariation of the fingers, i.e. the increase in individuated finger movements.

This review focuses on those studies using populations of pianists, either all professionals, or comparisons between professionals and novices. Studies solely involving novice pianists are omitted as these do not provide knowledge regarding refined technique. As individual differences between pianists are reported in the majority of the studies detailed, the review also looks only at those studies involving more than one pianist. In investigating the motions of piano touch technique, studies can be grouped into two categories: those which approach the analysis from a starting point of a compositional requirement e.g. the use of consecutive thirds, a set of chosen tempi, or a particular loudness level, and those which approach analysis from the starting point of the defined type of touch. To help clarify the terminology used in describing finger and hand motion, Figure 1 shows a diagram of the hand with anatomical terms regarding the rotations of the wrist, joint angles and movement of the fingers.

The motion generated to satisfy a compositional/expressive requirement

In terms of analysing the keypress movement used to achieve a particular compositional or expressive requirement, studies have shown that individual joint contributions in the keypress finger (Goebl & Palmer, 2013) and movement covariation between the striking and non-striking fingers in the metacarpophalangeal (MP) and proximal interphalangeal (PIP) joints (Furuya & Soechting, 2012) remain stable across performances of single tone right hand melodies at different tempi. This suggests that pianists are able to keep the independence of the fingers even as the rate of notes increases. An earlier study (Furuya, Flanders & Soechting, 2011) reporting no effect of striking finger on key velocity and minimal spillover from the motion of the striking finger to adjacent fingers corroborates the pedagogical idea of finger independence and equal strength across the hand.

The Effects of Tempo. Goebl and Palmer's (2013) study showed that throughout performances of single tone melodies at different tempi, the wrist supination/pronation and flexion/extension remained stable, whereas the finger joints experienced larger ranges of movement. Larger differences in the touch movement profile (i.e accelerations indicating a struck or pressed touch) were seen at slower tempi (Goebl & Palmer, 2008) whilst movement profiles became more similar at faster tempi, suggesting that slower tempi may give pianists the chance to use different types of touch. Increases in rate of finger-key acceleration peaks just before the finger-key contact (Goebl & Palmer, 2008) suggest that tactile information within each keypress is used to control time-keeping at these different rates. Preparatory finger height before the keypress also varies with changing tempo and dynamic requirements (Dalla Bella & Palmer, 2011). Although it may seem obvious to keep the fingers closer to the keys at faster tempi, this study suggests the contrary: in fact the height of the finger above the key may help pianists to keep in time. Finger identification of fingers 1 and 5 can be classified from the velocity-acceleration patterns of height before each keypress. This suggests that there are different characteristics for preparatory movements in fingers which are independent of the hand movement, different to fingers which are somewhat enslaved (like the middle and ring fingers) and more often rest on the key before the key press (Dalla Bella & Palmer, 2006). Results from these studies raise questions concerning the technique used, particularly whether the pianists have intended to retain equality of movement across all fingers, or are attempting to elicit different qualities of tone from using different fingers. Although the focus is often on the limitations of movement as tempo increases, the larger variations seen at slow tempi could indicate an influence of technique and/or expressive intention.

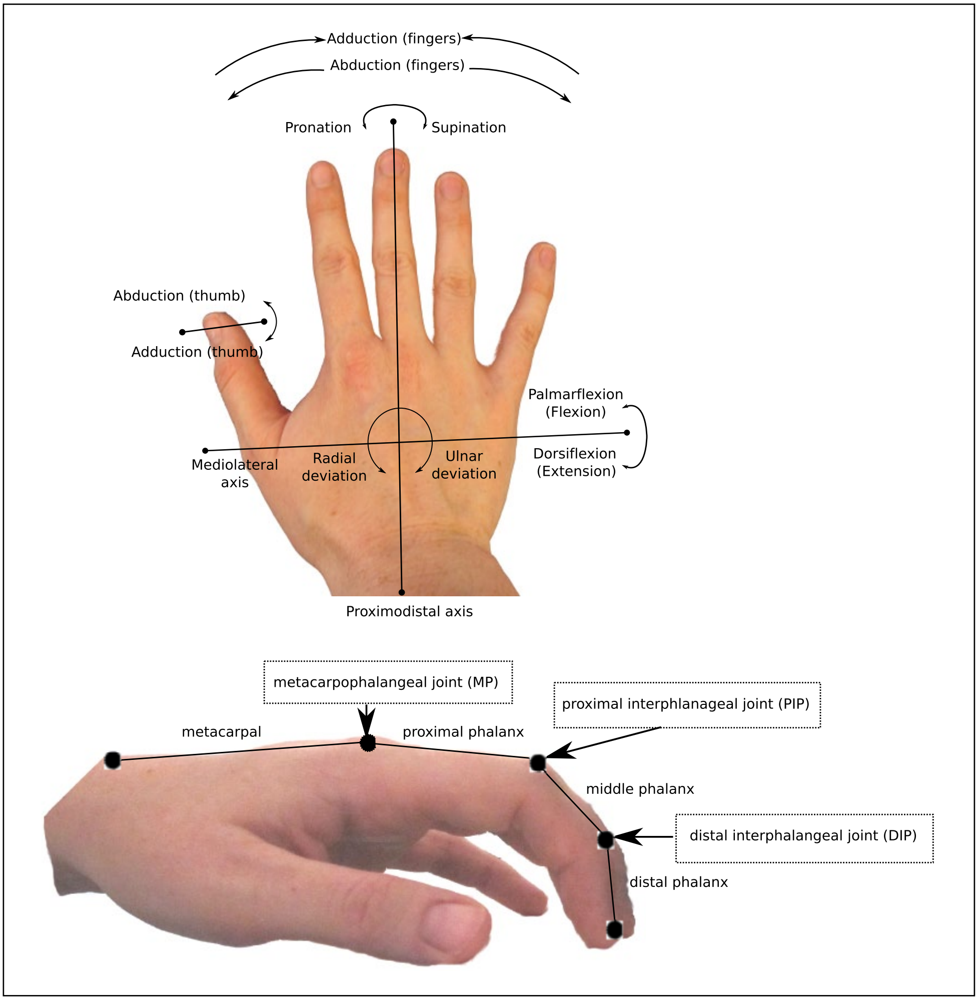

Figure 1. Terminology for hand rotations about the three axes, finger abduction (spread) and adduction, thumb abduction and adduction (rotation about a plane parallel to the palm), finger segment and joint names.

Comparing novices and professionals. The comparison of novice and professional pianists show the influence of training in the performance of various compositional features. For tremolo, i.e. a fast alternation between two notes, professional pianists demonstrate a reduction in muscular load when keeping the non-striking fingers lifted, as well as smaller extension angles in these non-striking fingers in comparison with novices (Furuya, Goda, Katayose, Miwa & Nagata, 2011). Moreover, professionals were more economic in the application (both strength and duration) of force for each keypress in a melody than novices (Parlitz et al., 1998) and less variable in terms of their keystrike force in the performance of repeated staccato octave chords (Furuya & Kinoshita, 2008). Professionals also showed less muscular torque at the MP, wrist and elbow, although increased torque at the shoulder in comparison with novice players. Repeating an octave chord at increasing loudness levels, the peak hand descending velocity changed for different levels of loudness. No difference in kinetic energy was seen across the groups of professionals and novices (Furuya & Kinoshita, 2007), although there was a clear difference in the kinematics of the arm downswing between the two groups (Furuya, Osu & Kinoshita, 2009).

These clear distinctions between novices and experts can quantify the effects of training, however, the smaller differences (and perhaps more meaningful differences for students and teachers) between groups of pianists with varying training and expertise are rarely explored. The difference between a staccato and legato note for pianists of varying skill levels (Harding, Brandt & Hillberry, 1989) showed few deviations in finger force across different key velocity levels. However, the range of forces seen at a given velocity would suggest that there are ways in which pianists can optimize their movements to use less force to achieve a similar result. Studies measuring 19 pianists' hand movements in a musical excerpt found differences between the professionals and the students and teachers in terms of the total kinetic energy used. (Ferrario et al., 2007). This study attempted to separate the movements necessary for the key-press from extraneous movements which could lead to injury, finding that the professionals had a greater amount of 'useful' kinetic energy per keypress than the students and teachers. Further exploration of the differences seen between groups of experts here may provide information on how to optimise keypresses for various compositional requirements. Repeatedly using more force than necessary to elicit an identical key velocity to that which could be produced by a key press with lesser force could eventually lead to injury.

Individual Differences. Although individual differences between pianists are often reported, potential contributing factors of hand anthropometry, technique and years of experience have yet to be thoroughly examined. Differences have been shown in pianists' kinematic profiles and extent of hand/finger rotations. Octave keypresses in a group of pianists with large hand spans showed a significantly larger maximum abduction angle of the thumb than a group of pianists with smaller hand spans, although the range of motion of this angle did not differ between groups. Pianists playing C major chords showed differences in maximum abduction angle and range of motion of the thumb, as well as for the little finger between groups of pianists with small hands compared to those with larger hand spans (Sakai et al., 2006). This suggests an influence of hand anthropometry on the pianist's technique.

Individual differences were found in the finger height velocity and accelerations of four pianists (Dalla Bella & Palmer, 2011), and in variations in velocity at all joints of the arm in eighteen pianists playing sixth chords (Furuya et al., 2012). In the latter study, these differences in performing staccato sixth chords were classified into three groups of pianists characterized by increasing/decreasing velocities at the finger, wrist, elbow and shoulder, suggesting that there may be influences in type of technique used in the movements exhibited by pianists for this particular compositional feature. Individual differences are expected for these pianistic tasks considering the high number of degrees of freedom within the hand. However, it is not known whether these differences are influenced somewhat by training and type of technique, although duration of the finger muscular activities may account for some variation (Winges, Furuya, Faber & Flanders, 2013). Different strategies appear to exist, although this is not yet linked to any intention on the performer's part. Although individual differences are likely to be a part of each pianist's distinctive 'sound', it can still be shown that touch, along with other aural parameters are manipulated to produce particular expressive requirements. Distinctly different profiles created from measurements in key angle (as a descriptor of touch), timing, articulation, pedalling and dynamics were shown to relate to specific timbral intentions, these performance features being consistent within a participant's set of repeated performances, yet distinctly different across performers (Bernays & Traube, 2014).

The motion generated by a particular touch definition or intention

A second category of studies concerns those that examine the differences in movement arising from differently defined touches, mainly the difference between struck or pressed. It is disputed whether audible differences in timbre can be produced from the difference between a pressed and struck touch, the most audible change being in the finger-key noise that is produced before the onset of the note. These finger-key noises are variable across pianists and may depend on the angle of attack of the finger (Goebl, Bresin & Galembo, 2004), with further study also confirming the effect of the sound of key-bottom impact on touch identification (Goebl, Bresin & Fujinaga, 2014). The sound produced at the point of finger-key contact may also contribute to the perception that a struck tone is louder than a pressed tone at the same measured decibel level (Furuya, Altenmüller, Katayose & Kinoshita, 2010). Different force profiles measured at the distal end of the key are used to characterise a pressed or struck tone, with individual differences that can be attributed to the differences in effective mass of the performer, i.e. the use of mass in the upper arm (Kinoshita et al., 2007). The authors find that a simple exponential function relates parameters of maximum force with the measured sound pressure level, regardless of the touch used, suggesting that the type of touch itself is not responsible for differences in loudness. Differences in struck or pressed touch can also be measured in the kinematics of various joints in arm movement (Furuya et al., 2010), with shoulder motion helping to increase the angle of the finger relative to the key when performing a 'struck' touch. Although the peak angular velocity of wrist flexion stays similar depending on type of touch, the finger joint was extended more and the attack angle of the finger with respect to the key was smaller at the onset of key depression for the pressed touch. There was a heavy reliance on the distal muscles for this touch compared to the struck touch, particularly at higher volumes of keypress. This inefficient use of muscles compared to the struck touch could contribute to overuse injuries in pianists, although it is acknowledged that the potential differences in perceived timbre make the combination of both touches useful in pianistic expression. The definitions of a struck versus a pressed touch describe the anticipatory motion of the hand before pressing the key. However, it is rarely acknowledged that there can be varying degrees of a struck touch depending on the initial velocity of the finger at the time of finger-key contact. The investigation of the influence of arm rotations, or the idea of 'weighting' within the arm might also be of more use to students and practitioners. Different postures and actions are proposed to perform passages of music, such as the difference between curved and flexed fingers, or variations in area of finger-key contact, such as the difference between using the fingertip or the pad of the finger, all which remain to be empirically tested (see Bermann, 2000, p.13 for an example where curved fingers are recommended for good articulation whilst flatter fingers are recommended to create a "singing sound of great warmth").

A few studies provide an exception, exploring the effect of different wrist postures, or the different aims of groups of pianists concerning the use of arm rotations. In terms of varying the wrist posture in piano playing between 'neutral', dorsi flexion and palmar flexion, muscle action in the wrist flexor and extensor is at its lowest in a wrist neutral position (Oikawa, Tsubota, Chikenji, Chin & Aoki, 2011). Chung and colleagues examined pianists using two types of technique: traditional and weight-playing (Chung et al., 1992). The latter group was stated as intending to increase rotations of the forearm and limit usage of the arm flexors and extensors. Pianists using traditional techniques showed more average motion in the wrist than pianists using weight techniques in performances of exercises and other classical pieces. On the other hand, trills and arpeggios required larger wrist flexion and extension for the weight players than the traditionals. Anthropometric measurements of the hand such as ulnar mobility (a measure of possible ulnar deviation) were also related to the tempo of playing consecutive thirds (Lee, 2010), suggesting it may have a role in allowing pianists to achieve such a compositional requirement.

Benefits and limitations of the state of the art

The limitations in these studies are often sample size and the spread of expertise. Large variations in technique used and individual differences in terms of hand anthropometry can also mean that wide generalisations can often not be made. The studies referenced in this section have been collated into Table 1, detailing the number, age, gender and expertise level of the participants, any measurements of hand span or classification of technique, repertoire performed, as well as a summary of the devices used to make measurements. Although these studies go some way in expanding knowledge concerning the kinematics of a keypress in various compositional conditions, we see only two studies (Chung et al., 1992; Oikawa et al., 2011) that aim to examine differences resulting from different approaches to playing the piano and three studies which contain some information regarding hand span measurements (Sakai et al., 2006; Furuya et al., 2009, 2011; DallaBella and Palmer's 2006 study mentions that there are no anatomical differences in hand size or shape). This goes some way to explaining the detachment seen between biomechanical knowledge and daily music instruction seeing as teachers (often using their own particular methods) frequently have to adapt to the requirements of different students. The large degrees of freedom in the hand, and thus the large number of different possibilities to press the key are compounded by limited sample sizes of experienced pianists (the largest of which is 19) of often varying expertise. Few studies classify the 'experts' into different groups based on years of training or performance experience, despite indications that this has implications for the movement patterns observed (Harding et al., 1989; Wolf, Keane, Brandt & Hillberry, 1993; Goebl & Palmer, 2008).

Of course what this literature does provide is an approximation to the average keypress in a number of conditions. When attempting to measure expressive movements, it is of the utmost importance to have a baseline of movements that can be considered entirely technical, so we can begin to pull apart the contributions from the physical requirements of the notes from the expressive requirements, and the individual interpretation provided by the performer.

Relating biomechanics knowledge to instrumental tuition

Despite the advances in knowledge regarding the biomechanics of the typical piano keypress amongst expert pianists, there remains a large gap in terms of incorporating these movement science findings into music pedagogy (MacKie, 2007; James & Cook, 2013). Books such as those clarifying the physiology of performing and potential injuries that can arise from bad technique (Watson, 2006), and those that debunk piano technique myths that are physiologically impossible (Brown, 2000) aid understanding across disciplines. However, few authors attempt to accurately relate these biomechanical findings to the level of instruction given in instrumental tuition. Wristen (2000) is one example that develops frameworks for analysing movements in particular exercises such as scales, broken chords and trills. Considering that there are high instances of injury that result from bad technique or overuse in pianists (Sakai, 1992, 2002) it is concerning that not more is known about different techniques and their

Table 1. Review of sample size and experience level, age, gender, ergonomics, and reported piano techniques along with repertoire used for the experiment, and measurement devices used. Study ordered by name of the first author. Studies from the same author using the same sample group, repertoire and/or devices are grouped together.

Reference	Subjects	Expertise	Age and Gender	Pedagogical Instruction	Repertoire	Device(s) used
Bernays and Traube (2014)	4	Professionals with advanced level performance diploma	1) F, 30yrs, French 2) M, 54 yrs, Italian 3) M, 46 yrs, French-Canadian 4) M, 22 yrs, French.	N/A	4 specially composed piano pieces (4-7 bars long, different meters, duration at score tempo 12-15 s). 5 timbral nuances to be expressed. 3 performances of each condition	Bösendorfer CEUS
Chung et al. (1992)	9	2 concert pianist professors of music, 7 graduate students (all more than 10 years experience)	N/A	Traditional (N=4) Weight playing (N=5) See in-text citation for definitions	Standard exercises (slow, fast and medium tempo),trills, arpeggios, octaves & broken octaves taken from excerpts of Beethoven & Tchaikovsky	Electro-goniometers attached to the wrists. Type of piano not reported.
Dalla Bella and Palmer (2006, 2011)	4	Different levels of musical expertise (mean 16.3 yrs, range 12-21 yrs experience) Performers 1 & 3 (mean 12.0 yrs), Performers 2 & 4 (20.5 yrs)	3F, 1M, mean age = 24 yrs, range = 18-40 yrs. No anatomical differences in hand size or shape.	N/A	Two 13-tone melodies performed with the right hand at different tempi (60, 180, 210, 240 & 250 beats per minute)	MIDI digital piano, Infrared motion capture.
Engel et al. (1997)	Not reported	Trained pianists	Not reported	N/A	Short excerpts from Rebikof, Bach & Kabalevsky	MIDI digital keyboard, optoelectronic motion capture.
Ferrario et al. (2007)	19	8 concert players,11 students and teachers, range 2-62 years of experience	5F, 14M mean age = 32.8 yrs, range = 8-69 yrs	N/A	Bach minuet (16 bar excerpt)	Bechstein grand pianoforte, infrared motion capture

Table 1. (Continued)

Reference	Subjects	Expertise	Age and Gender	Pedagogical Instruction	Repertoire	Device(s) used
Furuya and Kinoshita (2007, 2008a,b); Furuya et al. (2009	14 2008a:16	7 active expert pianists (more than 15 years classical piano training), 7 novices (less than 1 year piano training) 2008a: 8 active expert pianists, 8 novices, same conditions as above.	Experts: 4F, 3M, age = 24.3 ± 3.2 yrs; Novices: 4F, 3M, age = 21.0 ± 4.6 yrs 2008a: Experts: 5F, 3M, age = 24.0 ± 3.0 yrs; Novices: 5F, 3M, age = 20.6 ± 4.4 yrs 2009:hand span: Experts: 194 ± 4 mm, Novices: 195 ± 15 mm	N/A	Right hand octave staccato keystroke (G4 and G3) using the thumb and little finger. Four loudness levels (103, 106.5, 110 & 113.5 dB)	2007: Upright acoustic piano, two 2D position sensor systems (LEDs), sound-level meter 2008: Same as 2007 with addition of force transducer on key 2008a & 2009: Same as 2008 with addition of electromyography
Furuya et al. (2010)	7	Expert pianists (at least 15 years of classical-piano training, prizewinners at high-level domestic and/or international competitions)	4F, 3M, age = 24.3 ± 3.2 yrs	N/A	RH staccato keystroke of C3 by middle finger with struck and pressed touches. Two target loudness levels corresponding to maximum key-force levels: forte (9.6 N) and piano (4.4 N)	Yamaha U1 upright acoustic piano, two 2D position sensor systems (LEDs), sound-level meter.
Furuya et al. (2011a); Furuya and Soechting (2012)	5	Highly skilled pianists, prizewinners at national or international level.	2F, 3M, age = 33 ± 8 yrs	Pianists from different piano instructors	30 excerpts from 11 musical pieces, RH melody (Bach Preludes, Chopin Études & Moszkowski Études). Excerpts range from 9-24 notes (13.5 ± 2.8 notes)	MIDI digital piano, data glove, open at fingertips.
Furuya et al. (2011b)	10	5 Active expert professional pianists (more than 20 years formal classical training, national/international prizewinners) 5 amateur pianists (no history of musical education, practice for less than 3hr per week)	Professionals (3F, 2M, age = 24.3 ± 3.2yrs; hand span = 203.6 ± 15.1mm; body mass = 54.4 ± 13.6kg) Amateurs (2F, 3M, age = 22.6 ± 1.1yrs; hand span = 195.2 ± 15.1mm; body mass = 55.8 ± 9.8kg)	N/A	Repetitive tremolo keystrokes with RH (alternate keystrokes between E3 - thumb and C4 - little finger). Five tempi (70, 90, 110, 130 & 260 bpm).	MIDI digital piano, infrared motion capture system, EMG.

(Continued)

Table 1. (Continued)

Reference	Subjects	Expertise	Age and Gender	Pedagogical Instruction	Repertoire	Device(s) used
Furuya et al. (2012)	18	Music conservatory students or graduates (more than 15 years classical piano training)	13F, 5M, age = 30.2 ± 7.8yrs	N/A	RH repetitive staccato keystrokes of E4 (thumb) and C5 (little finger), i.e. major sixth. Four loudness levels corresponding to maximum keyforces 1.5, 2.7, 3.9 & 5.1 N.	Yamaha U1 upright, electromyography, two 2D position sensor systems (LED), force transducer on key.
Goebl et al. (2004, 2014)	2	2004: Not reported 2014: Studied piano at post-secondary level for 12yrs (Pianist 1) and 8 yrs (Pianist 2)	2004:Not reported 2014: Pianist 1 = 29 yrs, Pianist 2 = 34 yrs	N/A	Middle C played with struck or pressed touch.	Yamaha grand piano, two accelerometers attached to key and hammer shank, microphone.
Goebl and Palmer (2008)	12	Highly-trained pianists, majority university level (10-25 yrs piano lessons, mean 18.7 yrs).	Gender not reported, mean age = 27 yrs, range = 20-33 yrs	N/A	Two isochronous 16-tone melodies performed with the RH at different tempi (2, 4, 6 & 7 tones per second)	MIDI digital piano, Infrared motion capture.
Goebl and Palmer (2013)	12	Same as Goebl and Palmer (2008)	Same as Goebl and Palmer (2008)	N/A	One isochronous 5-tone melody performed at (7.0, 8.4, 9.6, 10.7, 11.7, 12.3, 13.3, 14.1, 15.0 & 16.0 tones per second)	MIDI digital piano, Infrared motion capture.
Harding et al. (1989)	4	Range of experience from 0-39 years.	1F, 3M, age = 31 ± 9.7yrs	N/A	Repetitive legato and staccato strikes of several white keys at two key locations (near extreme outer end of white key; close to end of adjacent black key) with increasing levels of loudness.	Yamaha digital piano, piezoelectric force transducer on key surface.

Table 1. (Continued)

Reference	Subjects	Expertise	Age and Gender	Pedagogical Instruction	Repertoire	Device(s) used
Kinoshita et al. (2007)	10	Active classical pianists (at least 15 years of training, prizewinners at high-level domestic and international competitions)	8F, 2M, age = 21.6 ± 1.7yrs	N/A	Repetitive 16th note keystrokes on one key C4; increasing loudness for 1st 15 keystrokes and decreasing loudness for next 15.	Force transducer on edge of the key, sound-level meter and 2D LED motion capture for key position.
Oikawa et al. (2011)	28	14 piano students (3.9 ± 1.4 years experience of classical piano playing, 15.7 ± 1.9 years of training) and 14 novices.	28F	3 wrist positions: neutral, 450 dorsiflexion & 200 palmar flexion.	10 staccato octave keypresses G3-G4 with RH thumb and little finger. Three loudness levels (pp: 73-76.9 dB; mf: 81-84.9 dB; ff: 89-93 dB).	Yamaha upright piano, sound-level meter, electrogoniometer, surface EMG.
Parlitz et al. (1998)	20	10 experts (average daily practice = 4h, average age beginning piano = 6 yrs) 10 amateurs (average daily practice < 1hr, age beginning piano range 5-20 yrs)	Experts: 5F, 5M; mean age = 23 yrs, range = 20-29 yrs) Amateurs: 3F, 7M; mean age = 29 yrs, range = 17-55 yrs)	N/A	3 tied-finger exercises (RH) - selected fingers (thumb & index; thumb, index & middle; thumb, index & ring finger) held down a chord for the entire exercise, while remaining fingers played other notes. Tempo: 60 bpm.	Steinway grand piano, sensor-matrix-foil applied underneath keys C-G.
Sakai et al. (2006)	10	5 professional and 5 amateur pianists. Group divided into 2 based on hand span measurements. Means were significantly different	6F, 4M, mean age = 29 yrs, range = 24-39 yrs. Group1: hand span = 24 ± 1.3cm; Group 2: hand span = 20 ± 0.6cm.	N/A	6 Octave keypresses (C - C) using thumb and little finger; 6 chord keypresses (C-E-G) using thumb, middle and little finger. Constant tempo.	Digital keyboard, video motion capture.
Wolf et al. (1993)	8	Injury-free professional pianists with experience 12-59 yrs (7 piano teachers, 1 professional with 12 years experience).	8M, age not reported	N/A	Mendelssohn's Song Without Words Op.19 No.2, performed once in entirety and once just with RH part.	Yamaha digital clavinova piano, 2 videocameras.

biomechanical constraints, as well as the effect of different piano characteristics (Allsop & Ackland, 2010), and that what is known is not better incorporated into everyday lessons.

Future Directions

To redress the gap between knowledge of piano touch in a biomechanical sense and artistic musical instruction, development in research must be seen from both sides. The first step is in the continual advance of new devices or systems that can be used both outside the laboratory and with a variety of different keyboard instruments. Easier incorporation of such technology into everyday lessons can also be encouraged by teachers and performers' involvement in specifying relevant parameters for visual feedback and participating in user studies to help shape user interfaces. Wider application of such measurements can then allow touch to be addressed on a greater scale considering larger numbers of pianists and across different types of piano. Initial studies could begin with comparisons of touch on acoustic versus digital pianos in a variety of performance venues in order to examine the contribution of different tactile and aural feedback on the action produced by the performer. This leads to the consideration of differences between upright and grand pianos and between different makes of piano. Greater inclusion of acoustic pianos in research would also allow measurements of the key-hammer mechanism, which in turn would provide opportunities for pianists to relate directly their manipulations of touch to the produced sound. In these new investigations we may view the full spectrum of movements that manifest in varying conditions, and the adaptations pianists have to make in response to the instrument and venue.

Taking the knowledge provided by studies of a typical keypress as a benchmark, we can then begin to separate the expressive properties of touch from the mechanical ones. In terms of general approaches to keypresses, examining the different effects of hand anthropometry and choice of technique on the finger-key action and associated arm movements could help establish the basis of movements possible and identify the particular areas that may contribute to injury through movements such as wrist over extension, or supination. Taking a deeper look into the variety of movements that can exist within a given approach to touch, performers may apply expressive intentions over groups of keypresses, manipulating minute changes in posture and movement to express structure such as phrases, or different moods/atmospheres. Examining how touch changes in the context of these varying concerns may ultimately aid teachers in instructing students how to achieve a variety of expression through touch whilst monitoring potentially damaging movements. This again requires the involvement of performers and teachers who can better define the intricacies of touch and aspects of sound that they are intending to produce. Their direction will ultimately help in the design and choice of measurement instruments that can be used to explore these fundamental questions. The challenge of this will be in finding a common language for artists and scientists to communicate in, acknowledging both the physical and experiential aspects that touch encompasses. The benefits of understanding the mechanics of movement behind a typical keypress and beyond are many: not only do students benefit in learning how certain actions of the arm joints aid in creating a particular hand gesture, but deeper knowledge of this action and the consequences for muscle/joint strain may ultimately lend a hand to injury prevention.

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