Hand Biomechanics in Skilled Pianists Playing a Scale in Thirds

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Pianists, who attend to the integral relationship of their particular musculoskeletal characteristics to the piano technique at hand, discover an efficient path to technical advancement and, consequently, to injury prevention. Thus, a study of pianist's hand biomechanics in relation to different piano techniques is highly relevant, as hand features may influence various techniques in different ways. This study addressed relationships between pianists' hand biomechanics and the performance of a scale in thirds, as a part of an ongoing series of studies examining relationships between hand biomechanics and performance data of primary techniques. The biomechanics of hand length and width, finger length, hand span, hand and arm weights, and ulnar deviation at the wrist were compared with tempo, articulation, and dynamic voicing (tone balance between two notes of the thirds). Pearson correlation analysis showed a positive association between ulnar deviation and tempo; the other biomechanical features showed no relationships with any of the performance criteria. Qualitative cross-sectional observation of individual profiles showed that experienced pianists perform with a higher degree of synchrony in two-note descent while pianists with organ training background play with a lesser degree of synchrony. All biomechanical features were closely related among one another with one exception: wrist ulnar deviation was not associated with any other biomechanical features; rather, data suggest possible negative associations. This study underscores the importance of wrist mobility in piano skills development. Further research using a complete set of prototype piano techniques and multiple-level pianist-subjects could provide substantive biomechanical information that may be used to develop efficient pedagogy and prevention strategies for playing-related injuries as well as rehabilitation. *Med Probl Perform Art* 2010; 25:167–174.

The study of modern piano technique has evolved from anatomical observation, the notion of kinematics and coordination, and biomechanics. Yet, many pianists today are hurried to achieve the end-results, the highest possible level of piano proficiency, often without taking into account their biomechanical characteristics. As a result, they may struggle blindly on acquiring techniques to the point of injury. It is not merely the drive to a high level of achievement coupled with the lack of a thorough basic technical preparation that trigger injuries, but a lack of biomechanical knowledge may cause one to deny the opportunity to develop the utmost efficiency in using their given biomechanical characteristics.

Ortmann[1] commented on the complexity and subtlety of individual differences in musical talents. He suggested that these differences "begin in the physiological variations of the gross physiological organism: the size of the hand, length of the fingers or arm, weight of the arm, and range of movements." [1(p297)] He noted that an adult pianist with a smaller hand and larger hand span (127°) had the pianistic advantage over a pianist with a large hand and smaller hand span (75°). A child's hand—generally featuring a small span between the thumb and index finger, high webs between fingers 2–3, 3–4, and 4–5, a small span between fingers 1 and 5, and a lesser range of movement at the wrist—is an example of a disadvantageous piano-playing hand. A same-age child with all the opposing biomechanical features made more rapid progress, possibly attributable to the biomechanical advantage.[1]

Kentner[2] pointed out that among famous pianists, Busoni, Rachmaninoff, Rosenthal, and Sauer had long fingers, while d'Albert, Reisnauer, Teresa Carreno, and Pachmann, had short ones. Richter could reach the 12th, while equally renowned Hofmann, only an octave.[3] It was noted that contrary to the legend, Liszt's fingers were not exceptionally long, yet his hands featured "deep-lying connective tissues between the fingers."[2(p20)] This remark about Liszt's superb piano-playing hands has been scientifically supported by Ortmann,[1] who observed that hands with high web between fingers are disadvantageous for piano playing because of the resulting lack of individuation.

Certainly, other physical characteristics influence the ability to perform at the piano. For instance, researchers have affirmed that joint mobility and finger spans, rather than hand size, are significant factors that impact piano performance.[4-7] On the other hand, finger mass does not seem to play an important role in tone production. Ortmann noted that pianists with "tapering" fingertips, who played with a "light, delicate touch," or pianists with a chubbier finger type, who produced a more massive tone, both had sufficient touch control and dexterity to produce the desired tones.[1]

Expert piano performance skill combines kinematics with the cognitive, spatiotemporal, and affective (interpretive) proficiency at the highest level.[8–10] Jerde and associates[11] observed the kinematics of finger movement during piano playing and equated the hand posture to similar hand movements that also involve covariations of the metacarpal and proximal interphalangeal (PIP) joints independently of the number of digits used (such as typing and whole-hand grasping). Although such equation is supported by anatomical considerations, a principal components analysis showed that higher-order principal components in the fine control of finger movements account for a small amount of the postural variability and superimpose on these simpler and more common patterns. The neural factors that activate selective hand muscles to produce the intended single or multiple

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digit motions are significant in the dexterous control of the hand. Accordingly, Jerde and associates[11] concluded, "the neuromuscular architecture of the hand might have evolved to allow the coordinated action of multiple digits rather than individual finger control. Hence it is not surprising that extensive practice is required to attain the exquisite dexterity and individuation of finger movement necessary to play a musical instrument."[11(p82)]

The notion of finger training in hand and arm coordination has been emphasized by famous piano pedagogues.[1,12-14] Seymour Bernstein[14] summed up the necessary coordination of finger and arm techniques: "Although all impulses in piano playing originate in your torso and upper arms, your fingers, nevertheless, assume the major share of responsibility for all that you play—even chords and octaves."[14(p152)] Fast notes played on one impulse, coined "ballistic movement" by Frank Wilson,[15] is a good example of the coordinated action of multiple digits. Significant finger strength and individuation are required to produce individual tones with clarity in fast movement.

Wagner[4] analyzed biomechanical data from 238 pianists and learned that 1) pianists' left hand spans were significantly greater than the right hand, and 2) ranges of both active and passive movements were greater in female than male. Lee[5] examined relationships of pianists' biomechanics of hand width, finger lengths, hand weight, arm weight, mobility at the metacarpophalangeal joint (MCP, finger spans), and wrist ulnar deviation with performance data of two technical exercises, an excerpt from Chopin's Etude Op. 10, No.1, and a Cortot's scale exercise with polyphonic tone with sustained fourth finger while playing five-finger scale. The study concluded that 1) wrist ulnar deviation was positively related to touch control of articulation and tempo, while 2) wrist ulnar deviation and hand weight were negatively related to the polyphonic tone control. The study also suggested that finger spans were positively related to both techniques, though findings were not statistically significant.[5]

In piano-related biomechanical and musical studies, researchers have used MIDI-based analysis to monitor practice effects on performance,[16] temporal and dynamic control,[5,17] dynamic finger forces,[18] and finger joint forces and tendon tension,[19] as well as interpretive and expressive aspects of piano performance.[20,21] These studies demonstrate the appropriateness of the MIDI technology to examine musical details of artistic precision, previously considered unthinkable.

The Study

Playing a scale in thirds with temporal evenness and dynamic control at a steady tempo requires strong and individuated fingers supported by a relatively relaxed arm. This study explored relationships between pianists' hand and arm biomechanics and the performance features. Twelve skilled pianists played a short excerpt of a "scale in thirds" exercise from Cortot's *Rational Principles of Pianoforte Technique* (1928)[22] on an electronic touch-sensitive keyboard. Performance data were recorded through the music instrument digital interface (MIDI), with the standard 96 clock-time unit and the standard 1–127 key velocity range.

METHODS

Pianists

The age range of the 12 pianists was 17 to 44 yrs, with the average age of 29. Pianists included a high school senior, 2 college piano minors, 1 organ major, 5 piano majors, 2 doctoral piano students, and 1 piano professor. Their years of study ranged from 8 to >30 with an average of 18 yrs. The sample consisted of 8 female and 4 male pianists. Pianist descriptions are given in the Appendix.

All pianists had the appropriate piano skills to play the double-note scale, access to the lab, and received the approval by the University of Alabama's Research Office to participate in the study (the Research Office oversaw the IRB process at the University). The researcher met individually with each pianist twice: first, to discuss specific performance goals (see below under performance data) and measure the hand and arm biomechanics; and second, after 2 wks of practice (about 20 times daily), to record the performance of the scale-in-thirds using a MIDI electronic piano. All pianists were asked to follow the 2-wk, 20-time daily regimen closely.

Hand Measurements

Pianists' biomechanics measurement was adapted from Wagner's method. Figure 1 shows Wagner's right hand measurement chart.[23] Active (unaided by an external force) *hand length* was measured from the base of the hand to the tip of the third finger. *Finger lengths* were measured from the MCP joint (dorsal) to the tip. A composite finger length was derived with the mean value of all five finger lengths. *Hand width* was the distance between the outer PIP of the thumb and the outer MCP of the fifth finger.

Active finger spans were measured in two ways: degrees of maximum active separation between each two fingers on a flat surface on a straight line, and finger spreads on the piano keyboard reach between each two fingers. Two sets of data were correlated to test validity; repeated measurements were taken to assure reliability. The *finger span 1–5* was composed from the aggregate of all spans between fingers 1 and 5: 1–2, 1–3, 1–4, 1–5, 2–3, 2–4, and 2–5. The aggregate *finger span 3–5* was computed to capture the limited structural characteristics of the fingers 3, 4, and 5 (new dimension in this study). This outer finger mobility of the fingers 3, 4, and 5 is particularly important in piano playing, as the salient melodic lines are often played with these fingers.[22,24]

Active *wrist mobility* in the ulnar side was measured on a flat surface volar-side down with the forearm held steady with the instantaneous center of rotation (ICR) of the wrist joint as the pivot point to measure the deviation angle. *Ulnar deviation* is considered essential in pianist's active biomechanics because ulnar deviation has limited support by the upper

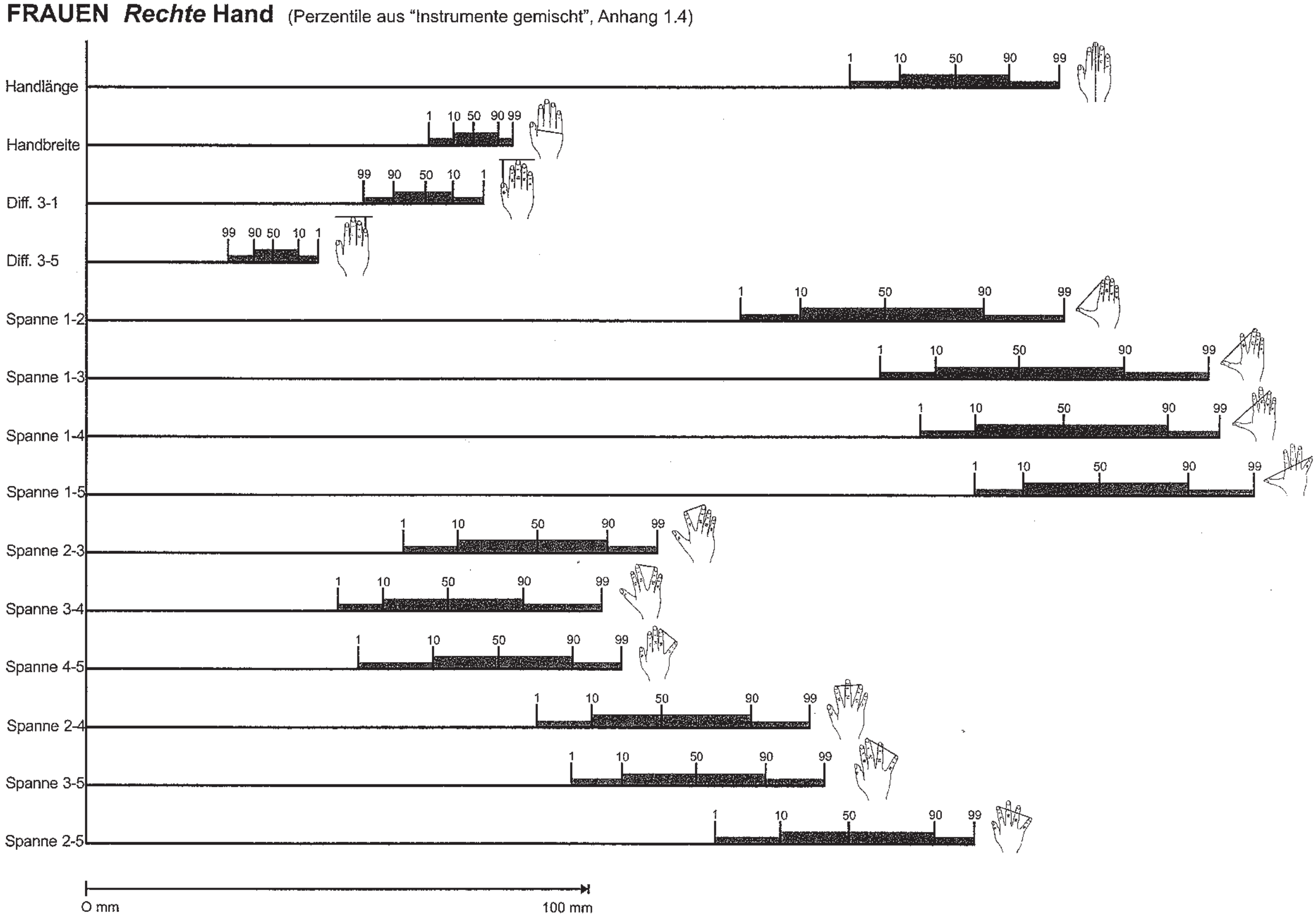

FIGURE 1. Wagner's right hand measurement chart (used with permission of Dr. C. Wagner).

arm and elbow abduction/adduction; contrarily, radial deviation is excluded in this study because it can be extensively supported by the elbow and upper arm abduction.

Hand and arm weights were measured, after a brief session of weight-relaxation training, in a level position (sitting position) with the scale on a tabletop. This gave the carrying hand and arm weights that pianists use rather than the "dead" arm weight. Since this was an innovative procedure, multiple measurements were made to test reliability.

Table 1 shows the complete measurements of pianist 1. Both left and right hand biomechanics were measured, but only the right had data were analyzed in the current study.

Measuring Performance

Each pianist played 16 sets of thirds in four beats with his or her preferred fingering in the right hand. All pianists recorded right-hand playing of the scale-in-fourth and scale-in-fifth exercises from Cortot's book during this session (Fig. 2). Only the recording of the scale in thirds played with the right hand alone was analyzed for the study. A 2-week, 20-times daily-practice regimen was followed by all pianists. Pianists did not feel the need to warm-up or take breaks in playing these short excerpts on the MIDI piano.

The intended musical aims were 1) to achieve legato in the top voice throughout, 2) to perform the top voice louder than the lower line, 3) to strive for simultaneous key descent of each two notes (synchrony), 4) to realize a *crescendo* in the rising line and a *decrescendo* in descending line and at the end of the phrase, and 5) to maintain even tempo. These musical aims were intended for artistic purpose rather than mechanical precision. Playing tempo was left to the individual, although tempo was considered as one of the performance criteria.

MIDI information includes note accuracy, onset and release time of each event (as measured by the standard 96 MIDI clock pulse), and key velocity (using the customary 1 to 127 MIDI range). Playing tempo is calibrated by first converting the playing time (TMCT, total MIDI clock time) to real-time playing of the 16 double notes; then metronomic playing tempo is determined by the number of quarter-note beats played in a real-time minute. The metronomic marking, MM (Maelzel's metronome), indicates the number of quarter notes played in a real-time minute. For instance, when the tempo is set at MM = 60, 60 quarter notes are played in 1 minute, which gives each quarter note value of 1 second (i.e., 1,000 ms) and the real-time MIDI clock pulse comes to 10.41 ms (1000 ÷ 96). When the tempo is set at MM = 100 (100 quar-

TABLE 1. Hand and Arm Measurements of Pianist 1

	Left	Right
Length (cm)		
Hand	15.3	15.3
Finger 1	5.5	5.5
Finger 2	7.7	7.6
Finger 3	8.7	9.1
Finger 4	8.0	8.8
Finger 5	6.3	7.1
Width (cm)		
Hand	9.4	9.0
Wrist	6.0	6.1
Finger Span (cm)		
Fingers 1–2	15.5	15.0
Fingers 1–3	17.7	17.1
Fingers 1–4	19.2	18.3
Fingers 1–5	19.4	19.4
Fingers 2–3	8.2	8.4
Fingers 2–4	10.75	11.0
Fingers 2–5	13.7	13.7
Fingers 3–4	6.0	7.0
Fingers 3–5	9.0	11.7
Fingers 4–5	6.0	7.4
Wrist mobility (deg)		
Radial direction	10	8
Ulnar direction	40	38
Weight (lbs)		
Hand	1.75	1.75
Forearm	4	3
Whole arm	5	4.5

ter notes played in 60 s, each quarter note value, 600 ms), the real-time MIDI clock pulse comes to 6.25 ms (600 ÷ 96).*

Legato playing is calculated in direct relation to the percentage of a momentary overlap between key off and the next key onset timing. *Voicing* is measured by calculating the percentage of the average difference of key velocities of upper and lower notes of all thirds. *Synchrony* was the key onset timing of each third monitored by MIDI event clock time. Range and the average time lapse between two notes are hand calculated to measure *asynchrony*. Dynamic range is based on the MIDI key velocity (KV) range of 1–127. The higher rate of legato, voicing, and synchrony, a greater dynamic range, and relatively faster and even tempo are the targeted performance aims.

Biomechanics and Playing Data Analyses

Simple descriptive statistics were used to show the variability among the 12 pianists. Two-tailed Pearson correlation analyses were performed for quantitative comparisons among all bivariate biomechanics variables and between biomechanics and performance variables. Qualitative observation of 12 profiles provides additional insights. Table 2 shows the 12 pianists' biomechanics and performance profiles.

RESULTS

Descriptions

Biomechanics: Simple description in Table 3 shows that hand lengths ranged from 15.3 to 20.6 cm, with the average length of 17.7 cm. Hand width ranged from 9 to 11.85 cm, with the mean width of 10.5 cm. Finger length ranged from 7.61 to 9.33 cm, with the average 8.56 cm. Composite finger span 10–5 ranged from 13.3 to 18.87 cm with the mean 16.21 cm. The composite finger span 3–5 ranged from 8.3 to 12.13 cm with the average 9.8 cm. Wrist ulnar deviation ranged from 27.5 to 50° with the average of 35.5°. Hand weight ranged from 1.5 to 3.5 lbs with the average weight of 2.19 lbs, and arm weight ranged from 4.5 to 8 lbs with the average weight 6.59 lbs. While the ranges are broad in all measures, there were no extreme outliers in any of the biomechanics variables.

Biomechanics Correlations

Two-tailed Pearson correlation statistics shown in Table 4 indicates that hand length is positively related to hand width, finger length, and finger span 1–5, finger span 3–5, and arm weight. Hand width is positively correlated with finger length, finger span 1–5, finger span 3–5, and hand and arm weights. Finger length is correlated to finger span 1–5, finger span 3–5, and hand and arm weights. Finger span 1–5 is correlated with finger span 3–5 and arm weight. Conspicuously, ulnar deviation is correlated with none of the hand and arm biomechanics, even suggesting negative relations with all of them. Arm weight is positively correlated to all hand features (except wrist ulnar deviation), while hand weight is positively related to only hand width and finger length. This indicates that, while hand and arm weights generally correlate, there are some variations in proportion between hand and arm weights among the individuals.

Biomechanics and Performance

Bivariate analysis of biomechanics and performance data shown in Table 5 indicates a significant correlation between

FIGURE 2. Cortot's exercise on harmonic thirds.

*Quarter note value in real time at tempo (MM = 100) = 60 ÷ 100 = 0.6 seconds (600 ms).

1 MIDI clock pulse value in real time at (MM = 100) = 0.6 ÷ 96 = 0.00625 seconds (6.25 ms).

Mean quarter-note value in real time = TMCT (total MIDI clock time) × 0.00625 ÷ 4.

Player's tempo = number of quarter notes played in real-time minute.

Player's tempo formula: MM = 60 ÷ (TMCT × 0.00625 ÷ 4).

TABLE 2. Pianists' Profiles

	Pianist											
	1	2	3	4	5	6	7	8	9	10	11	12
Gender	F	F	M	F	F	F	F	M	F	M	M	F
Age (yrs)	27	21	40+	37	35	38	17	32	22	21	23	30+
Piano study (yrs)	22	14	30+	30	8	25	11	17	14	15	8	17
Profession	Performer	Performer	Professor	Performer	Minor	Performer	Performer	Minor	Performer	Performer	Organist	Performer
Biomechanics data												
Hand length (cm)	15.3	17.1	18.6	18.1	16.0	18.4	16.9	18.0	18.1	20.6	18.1	17.6
Hand width (cm)	9.0	9.3	11.5	10.6	9.4	10.7	9.0	11.3	10.6	12.3	11.85	10.7
Finger length (cm)	7.61	8.12	9.12	8.82	7.76	8.46	8.60	8.50	8.90	9.33	8.80	8.72
Finger span 1–5 (cm)	14.70	16.00	17.17	14.68	13.30	15.82	15.37	17.45	15.85	17.74	17.67	18.87
Finger span 3–5 (cm)	8.70	8.80	11.18	8.68	8.30	10.00	10.43	10.20	9.83	12.13	11.13	10.55
Wirst-ulnar deviation (deg)	38	45	50	39	32.5	27.5	40	30	30	30.5	30	33
Hand weight (lbs)	1.75	1.5	3.5	2.75	2.0	2.0	1.5	2.5	1.75	2.5	2.5	2.0
Arm weight (lbs)	4.5	6.0	8.0	6.0	5.0	8.0	5.5	7.6	6.5	8.0	8.5	5.5
Tempo*												
TMCT	606	572	553	701	889	813	647	977	880	1095	866	709
MM	63.37	67	69.44	54.79	42.1	47.23	59.35	39.3	43.65	35.07	44.35	54.16
Legato (%)	94	90	69	37.5	25	87.5	94	63	75	90	75	94
Asynchrony												
Range (ms)	0-75	0-19	0-13	0-25	0-44	0-19	0-50	0-31	0-38	0-38	0-31	0-31
Average lapse time (ms)	10.95	5.08	7.0	7.8	14.85	7.03	16.0	10.55	10.55	10.9	19.13	10.15
Dynamics												
Range KV†	55-80	52-83	57-83	43-73	52-80	50-78	53-73	44-66	44-65	48-75	42-66	56-85
SD	6.0	4.31	5.94	6.62	6.38	6.25	4.63	6.19	5.81	4.38	5.94	9.5
Topnote louder (%)	62.5	67.0	62.5	68.75	56.25	87.5	87.5	43.75	75.0	62.5	62.5	93.75

*TMCT, total music clock time; MM = 60 ÷ (TMCT × 0.00625 ÷ 4).
†KV range 1–127: approx 50 = p, 66 = mp, 78 = mf, 90 = f, 110 = ff.

tempo and ulnar deviation (0.886, p=0.01), while all other biomechanical features suggest negative association with tempo. Besides ulnar deviation, there are no other correlations between hand biomechanics and performance. Bivariate data among the music variables show no significant correlations among performance indicators.

Qualitative Observation

Arm weight: Pianists 3, 6, 8, 10, and 11, with heavier arms, did not show any common pattern in their performance outcome.

Gender: Male pianists generally featured larger hands with wide spans but not necessarily an enhanced ulnar wrist mobility. No other gender-specific patterns emerged.

Asynchronous gap between the two notes in the scale of thirds: More experienced pianists (pianists 2, 3, and 6 with 14, 30, and 25 yrs, respectively) played with better synchrony. The profile of pianist 1 shows the largest asynchrony range (75 ms), and pianist 11, the largest deviation in synchrony (19.13). Presumably, these two organists/pianists transferred organ technique, where asynchrony is used to achieve tone emphasis, compensating for the lack of touch-control mechanism (key velocity) in the organ.

Dynamic range: None of the biomechanics or performance factors seems attributable to the variation in dynamic range.

Tempo variation: Pianists chose their own tempo, while targeting other performance aims. Interestingly, while tempi varied considerably among the 12 pianists (range, MM = 40 to 70), it did not affect other musical variables. In other words, pianists who played with faster tempo did not sacrifice other desired musical aims.

DISCUSSION

This study illuminates that pianists' hand biomechanics are positively correlated among the various features except for ulnar deviation. Correlation between hand and arm weights is positive, but relationships of hand and arm with other biomechanical features are varied, indicating that some pianists have a heavier arm with lighter hand while others may have the opposite proportion. In other words, the proportion between hand and arm was not consistent among the 12 pianists.

Ulnar deviation was not related to any other biomechanical measurements, even suggesting possible negative associations with all hand variables. The only significant positive association between biomechanics and performance was the positive relationship between ulnar deviation and tempo.

TABLE 3. Biomechanics Statistics for the 12 Pianists

Variable	No.	Mean	SD	Median	Min	Max
Hand length (cm)	12	17.73	1.34	18.05	15.3	20.60
Hand width (cm)	12	10.52	1.13	10.65	9.0	12.30
Finger length (cm)	12	8.56	0.52	8.66	7.61	9.33
Finger span 1–5 (cm)	12	16.21	1.60	15.92	13.3	18.87
Finger span 3–5 (cm)	12	9.99	1.19	10.10	8.3	12.13
Ulnar mobility (deg)	12	35.45	6.97	32.75	27.5	50.00
Hand weight (lbs)	12	2.18	0.59	2.00	1.5	3.50
Arm weight (lbs)	12	6.59	1.37	6.25	4.5	8.50

Contrarily, data suggested negative relationships between all biomechanics variables and tempo. None of the other performance variables, articulation, dynamic voicing, or synchrony, all important attributes to achieve musical quality, was influenced by hand biomechanics. This is consistent with Ortmann's observation that trained pianists, either with light and tapered fingers or with chubbier hands, both accomplish the desired tones.

This report is a part of an exploratory study which experimented with a series of carefully selected technical excerpts played by 12 (13 in previous report[5]) skilled pianists. I began the study with some preconceptions but with no set hypotheses. Previous empirical studies[1,4] have revealed positive relationships among joint mobility, finger span, and skilled piano playing; but the prominent role of wrist deviation in the ulnar direction in skilled piano playing was not anticipated. Further, the lack of correlations between all hand biomechanics and wrist ulnar deviation and the nonrelationship of all hand biomechanics (except wrist ulnar deviation) in playing the scale in thirds were not expected.

Leijnse and his team[27] studied musicians' anatomical restrictions of bidigital finger system and questioned whether certain stretch exercises can permanently improve finger independence. They considered finger independence primarily as a function of disconnection between tendons that allows larger extension. Such separation of anatomical function is problematic. Some well-known pedagogues of the past taught exercises involving high individual finger lifting to increase finger independence (e.g., my own teacher, the famous pedagogue Aube Tzerko of UCLA and Aspen School of Music). Informed by numerous anecdotal testimonies, today's pedagogues are well aware that these exercises may cause serious injury. Rather, finger individuation is developed by whole arm–finger coordination, conditioning the timing of finger flexion, building strength of intrinsic muscles between fingers, enabling steady musculoskeletal fixation at the MCP and interphalangeal joints, strengthening extrinsic muscles of the forearm, and conditioning the shoulder and upper arm. In this light, Jerde's approach to neurological digit–hand coordination is more appropriate.[11]

Kentner witnessed many good piano pedagogues teaching students with most unlikely looking hands to play virtuosic piano by requiring intense exercises to stretch an octave (or more) and widen gaps between fingers.[2] This may be because, joint mobility, finger spans, and touch control can be developed by properly balancing arm and hand weight as part of pianists' technical development, regardless of the more rigid bone structure and other static features of the hand.

Artistic precision and scientific precision are conceptually disparate; playing scales in thirds with mechanical precision would not only be biomechanically awkward but also musically undesirable. Hence, looking at the detailed musical aspects is imperative in scientific study involving music performance. Individual biomechanics and performance profiles inform the researcher about unique connections between the body and performance outcome as controlled by individual pianists. Sakai and his colleagues[26] noted many variations among individual pianists and their techniques. Pianists in this current study used coordinated finger and weight techniques to play the scale-in-thirds exercise. It

TABLE 4. Correlation Matrix Among Biomechanics Measurements

	Hand Length	Hand Width	Finger Length	Finger Span 1–5	Finger Span 3–5	Ulnar Deviation	Hand Weight	Arm Weight
Hand length	1	**0.868†**	**0.896†**	**0.605***	**0.767†**	–0.210	0.528	**0.799†**
Hand width		1	**0.793†**	**0.702†**	**0.766†**	–0.32	**0.718†**	**0.858†**
Finger length			1	**0.635***	**0.8†**	–0.032	**0.56***	**0.676†**
Finger span 1–5				1	**0.796†**	–0.133	0.329	**0.575***
Finger span 3–5					1	–0.149	0.428	**0.72†**
Ulnar deviation						1	0.228	–0.226
Hand weight							1	**0.592***
Arm weight								1

*Correlation is significant at the 0.05 level (2-tailed).
†Correlation is significant at the 0.01 level (2-tailed).

TABLE 5. Correlation Between Performance and Biomechanics Measurements

	Tempo	Legato	Voicing
Hand length	−0.42	0.12	0.00
Hand width	−0.05	−0.02	−0.22
Finger length	−0.23	0.13	0.16
Finger span 1–5	−0.14	0.5	0.12
Finger span 3–5	−0.27	0.44	0.10
Ulnar deviation	0.89*	0.03	−0.04
Arm weight	−0.36	0.08	−0.19
Hand weight	−0.02	−0.38	−40

*Correlation is significant at p=0.01.

demonstrated that skilled pianists create solutions to different piano technical problems by applying their unique set of biomechanics to achieve proficient performance. To this end, knowing one's hand biomechanics would be very useful in developing efficient skills for various techniques.

Current piano pedagogy maintains that the essential requirement of skilled piano-playing lies ultimately in the mind.[28,29] A study of the mind-body connection can be further explored as we gain more facts about pianists' biomechanics and their relationship with skills development. Meanwhile, pedagogues could benefit by considering individual pianist's hand features as they assign appropriate technique and repertoire at various developmental stages in order to ensure efficient skills development as well as injury prevention. Such biomechanical strategy could also be helpful in rehabilitation of injured pianists.

Results of this study underscore the importance of ulnar deviation in playing scales in thirds, affirming the findings of previous studies in relation to the function of joint mobility in piano playing.[1-3,5,6,25] However, the implication of this study is limited due to the small, self-selected purposive, convenient pianist sample. This study provides a compelling model, however, that can be replicated and expanded by using a larger sample of pianists with a comprehensive set of prototype piano exercises. At the same time, this exploratory study generates a useful hypothesis for teachers to encourage students to develop wrist flexibility, which, importantly and undoubtedly, requires incipient relaxed arm and hand. As a postscript, I must profess that science in piano techniques study does not precede the age-old practice of the few well-regarded pedagogues; science helps to affirm the good pedagogy and gives tools to separate the misguided pedagogy.

REFERENCES

1. Ortmann O: The Physiological Mechanics of Piano Technique. London, Kegan Paul, Trench, Trubner & Co., Ltd., 1929. (Paperback reprint: New York, EP Dutton and Co., 1962, and New York, Da Capo Press, 1984.)
2. Kentner L: Piano. New York, Schirmer Books, 1976.
3. Rosen C: Playing the Piano. NY Rev Books, Oct 21, 1999, pp49-52.
4. Wagner C: The pianist's hand: anthropometry and biomechanics. Ergonomics 1988; 31(1):97-131.
5. Lee SH: Pianists' hand ergonomics and touch control. Med Probl Perform Art 1990; 5(2):72-78.
6. Chung IS, Ryu J, Ohnishi N, et al: Wrist motion analysis in pianists. Med Probl Perform Art 1992; 7(1):1-5.
7. Schuppert M, Wagner C: Wrist symptoms in instrumental musicians: due to biomechanical restrictions. Med Probl Perform Art 1996; 11(2):37-42.
8. Palmer C: Music performance. Annu Rev Psychol 1997; 48:115-124.
9. Clarke E: Understanding the psychology of performance. In Rink J, ed. Musical Performance: A Guide to Understanding. Cambridge, Cambridge Univ. Press, 2002.
10. Jabush HC: Movement analysis in pianists. In Altenmüller E, Wiesendanger M, Kesselring J, eds. Music, Motor Control and the Brain. New York, Oxford Univ. Press, 2006.
11. Jerde TE, Santello M, Flanders M, Soechting JF: Hand Movements and musical performance. In Altenmüller E, Wiesendanger M, Kesselring J, eds. Music, Motor Control and the Brain. New York, Oxford Univ. Press, 2006.
12. Gieseking W and Leimer K: Piano Technique: The Shortest Way to Pianistic Perfection and Rhythmics, Dynamics, Pedal and Other Problems of Piano Playing. New York, Dover Publications, 1972.
13. Schultz A: The Riddle of Pianist's Fingers: And Its Relationship to a Touch Scheme. New York, Carl Fischer Inc., 1949.
14. Bernstein S: With Your Own Two Hands: Self Discovery Through Music. New York, Schirmer Books, 1981.
15. Wilson FR: Mind, Muscle and Music: Physiological Clues to Better Teaching. Elkhart, IN, The Selmer Comp., 1981.
16. Highben Z, Palmer C: Effects of auditory and motor mental practice in memorized piano performance. Bull Council Res Music Educ 2004; 159:58-65.
17. Repp BH: Relational invariance of expressive microstructure across global tempo changes in music study: an exploratory study. Psyhol Res 1994; 56:269-84.
18. Parlitz D, Peschel T, Altenmüller E: Assessment of dynamic finger forces in pianists: effects of training and expertise. J Biomech 1998; 31(11):1063-1067.
19. Harding DC, Brandt KD, Hillberry BM: Minimization of finger joint forces and tendon tensions in pianists. Med Probl Perform Art 1989; 4:103-108.
20. Shaffer LH: Musical performance as interpretation. Psychol Mus 1995; 23(1):17-38.
21. Repp BH: Patterns of expressive timing in performances of Beethoven minuet by nineteen famous pianists. J Acoust Soc Am 1990; 88:622-641.
22. Cortot A: Rational Principles of Pianoforte Technique. Paris, Edition Maurice Senart, 1928. (Reprint: Paris, Éditions Salabert, Inc., 1972.)
23. Wagner C: Hand und Instrument: Musikphysiologiesche Grundlagen Pracktische Konsequenzen. Weisbaden. Leipzig, Breitkopf & Hårtel, 2005.
24. Lee SH: A Psychophysiologial Approach to the Technical Problems Found in the Piano Etudes of Chpoin and Liszt and a Compendium of the Solutions [dissertation]. Athens, GA, The University of Georgia, 1977.
25. Sakai N, Liu MC, Su FC, et al: Motion analysis of the fingers and wrist of the pianist. Med Probl Perform Art 1996; 11(1):24-29.
26. Sakai N: Hand pain related to keyboard techniques in pianists. Med Probl Perform Art 1992; 7(2):63-65.
27. Leijnse JN, Snijders CJ, Bonte JE, et al: The hand of the musician: the kinematics of the bidigital finger system with anatomical restrictions. J Biomech 1993; 26(10):1169-1179.
28. Neuhaus H: The Art of Piano Playing. (Leibovitch KA, transl.) New York, Praeger Publ., 1973.
29. Kochevitsky G: The Art of Piano Playing: A Scientific Approach. Princeton, NJ, Summy-Birchard Music, 1967.

APPENDIX: PIANIST DESCRIPTIONS

Pianist 1 is a 27-year-old female graduate piano performance major with 22 years of keyboard playing both on the piano and church organ. This pianist's hand biomechanics shows the average hand lengths, spans, weight, and mobility among the 12 pianists. Performance data indicate total playing time of 606 TMCT and playing tempo of MM = 63.37. She has good control of legato playing (94%), voicing (72.5%), and dynamics (a range is 55 to 80 KV with an average deviation of 6). Asynchrony of two notes is wide (0 to 75 ms) with an average deviation of 10.95 ms, which may be attributable to her training as an organist. In organ playing, asynchronous key attack is used to emphasize important notes to compensate for the lack of the dynamic touch control mechanism.

Pianist 2, a 21-year-old female doctoral student with 14 years of training, aspires to become a college faculty-level performer. She has larger (17.1 and 9.3 cm) and lighter hand (1.5 lbs) with slightly heavier arm (6 lbs) than the previous pianist. She also has wider finger spans (16 and 8.8) and better wrist mobility (45°). Her performance has smaller harmonic asynchrony (0–19 ms) and slightly faster tempo (MM = 67).

Pianist 3 is a male university piano professor with over 30 years of serious piano playing. He has significantly larger (18.6, 11.5, and 9.12 cm) and heavier hand and arm (3.5 and 8 lbs) with wider spans (17.17 and 11.18 cm) and large wrist mobility (50°). He played with faster tempo (MM = 69.44) and smaller asynchrony (0–13 ms). This profile demonstrates a strong association of favorable biomechanics and longer performance experience with good performance outcomes.

Pianist 4, a 37-year-old female doctoral student, has large (18.1, 10.6, 8.82 cm) and heavy hand and arm (2.75 and 6 lbs) with smaller outer 3–5 finger span (8.68 cm) and relatively small wrist ulnar deviation (39°). This playing shows slower tempo (MM = 54.79), less consistent legato (37.5%), and moderate dynamic range (43–73 KV). Despite the large hand and over 25 years of training, proportionately smaller outer finger span and small wrist ulnar deviation seem to be associated with slower tempo and lesser touch control. Tension might be related to the lack of flexibility and smaller hand span for this large-handed pianist. Conversely, we can also speculate that lack of wrist mobility and small outer hand span may be the cause of tension.

Pianist 5 is a 35-year-old female with 8 years of training. She has the average hand size (16, 9.4, and 7.76 cm) and finger spans (13.3 and 8.3 cm) with smaller ulnar deviation (32.5°). Performance data show considerably slower tempo (MM = 42.1) and less legato control (25%). Harmonic asynchrony is broad (0–44 ms with mean deviation 14.85 ms), but the dynamics are closer to the intended range (52–80 KV) with small deviation (6.38 mean deviation).

Pianist 6, a 38-year-old female performer with 25 years of training, has long hand and fingers (18.4 and 8.46 cm) and wide spans (15.82 and 10 cm), but with considerably smaller ulnar deviation (27.5°) and heavier arm (8 lbs). She plays with relatively slower tempo (MM = 47.23), good legato control (87.5%), small range of asynchrony (0–19 ms), and good voice control (87.5%).

Pianist 7, a 17-year-old female pianist with 11 years of training, has favorable biomechanics with large ulnar mobility (40°) and lighter hand and arm (1.5 and 5.5 lbs). Her performance data indicate good tempo (MM = 59.35), moderate dynamic range (53–73 KV) and synchrony (0–31 ms), demonstrating a good control in all intended performance aims.

Pianist 8 is a 32-year-old male pianist with a minor in music with 17 years of training. He has large hand (18, 11.3, and 8.5 cm) with wide span of 1-5 (17.45 cm), but small 3–5 span (10.2 cm) and small ulnar deviation (30°). Performance data show slower tempo (MM = 39.3), smaller dynamic range (44-66 KV), with uneven voice control (43.75%). In addition to small 3–5 span and small ulnar deviation, as a minor in music, this pianist may have trained less rigorously than other performance majors.

Pianist 9 is a 22-year-old female performer with 14 years of training. She has large hand (18.1, 10.6, and 8.9 cm) with good size finger spans (15.85 and 9.83 cm), but small ulnar deviation (30°). The performance data show good touch control both temporally (75% legato playing) and dynamically (75% louder top-voicing). However, the tempo is slower (MM = 43.65) and dynamic range is small (44–65 KV).

Pianist 10, a 21-year-old male performer with 15 years of training, has the largest hand (20.6, 12.3, and 9.33 cm), finger spans (17.74 and 12.13), and hand and arm weights (2.5 and 8 lbs) in the group, but with unexpectedly small ulnar deviation (30°). Tempo is the slowest (MM = 35.7) and dynamic range is moderate (48-75 KV).

Pianist 11 is a 23-year-old male organist with 8 years in keyboard training. This is another case of large hand (18.1, 11.85, and 8.8 cm), wide spans (17.67 and 11.13 cm), heavy hand and arm (2.5 and 8.5 lbs) with small ulnar deviation. Performance shows slower tempo (MM = 44.35) and smaller dynamic range (42–66 KV). Touch controls in legato (75%) and voicing (62.5%) are moderate; however, synchrony has wide deviation (19.13 ms). This subject is primarily an organist, which may contribute to the large deviation in asynchrony, as is the case with a large range of asynchrony in Pianist 1 with church organ background.

Pianist 12, 32-year-old female with 17 years of training, has good size hand (17.6, 10.7, and 8.72 cm) with the largest finger span 1–5 (18.87 cm) and relatively good finger span 3–5 (10.55 cm). She has relatively small ulnar deviation (33°) and lighter hand and arm (2 and 5.5 lbs). Her tempo (MM = 54.16) and articulation (0–31 ms) are moderate. However, she has the best legato and voicing (legato 94% and top voice control 93.75%) and wide dynamic range (56–85 KV).