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 s

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

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 1…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

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:

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.[3] 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] tested 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•

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.

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