Minimization of Finger Joint Forces and Tendon Tensions in Pianists

David C. Harding, Kenneth D. Brandt, M.D., and Ben M. Hillberry, Ph.D.

Abstract—High-level musicians, especially pianists, frequently develop musculoskeletal problems and pain in their fingers and hands. A better understanding of the biomechanical factors relevant to piano playing may be helpful in preventing performance-related injuries. In the present study a mathematical model based on finger anatomy was used to determine finger tendon tensions and joint reaction forces for specific finger positions and input fingertip forces. The magnitude of dynamic fingertip/key force was measured indirectly by calibrating a digital electronic piano with a piezoelectric force transducer. The model equations were then solved repeatedly in a non-linear optimization routine to determine the finger positions yielding minimum tendon and joint forces. In general, use of a more curved finger position, with a large metacarpophalangeal joint flexion angle, reduces flexor tendon tensions and thus resultant forces in the finger joints. Med Prob Perform Art 4:103–108, 1989.

Performance-related health problems have plagued professional musicians for centuries. Many of the musculoskeletal problems they encounter appear to be due to technique, working conditions, or the basic awkwardness of holding or playing the instrument. Musculoskeletal complaints are commonly due to tendinitis, overuse syndrome, and upper extremity nerve entrapment (e.g., carpal tunnel syndrome at the wrist, radial nerve compression at the elbow).1-3 Although physicians can often readily diagnose these conditions, a clear understanding of how the mechanics of playing the instrument affect forces on the joints, tendons, ligaments, and muscles is lacking. Elucidation of the relevant mechanics, therefore, may ultimately be helpful in prevention and management of performance-related injuries.

The objectives of the present study were to identify some of the biomechanical factors important in piano playing and to develop a quantitative database of these factors which might be used to compare and contrast performance techniques in "normal" musicians and those with performance-related musculoskeletal complaints.

Piano performance was chosen for study because pianists commonly experience musculoskeletal problems,1-3 and the majority of upper extremity movement during piano playing can be described as two-dimensional. Also, digital pianos are available which can be used to provide information needed to determine the input force to the fingertip during piano playing. In the present study a mathematical model of the finger was developed and utilized in conjunction with a force-calibrated digital piano to determine the finger positions that minimize biomechanical tensions in tendons and joint forces during piano playing.

MATERIALS AND METHODS

The Piano

The instrument used for this study was a digital piano (Yamaha CLP-300 Clavinova) with touch-sensitive keys weighted similarly to those of a standard acoustic piano. The electronic circuitry of the digital piano provides key velocity information which corresponds directly to the acoustic output (loudness). On the instrument employed, the key velocity varies from a (unitless) magnitude of 15 (softest) to 127 (loudest).

A mathematical model of the finger was developed and utilized in conjunction with a force-calibrated digital piano to determine the finger positions that minimize biomechanical tensions in tendons and joint forces during piano playing.

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TABLE 1. Subjects Participating in Study

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Piano Playing Experience (years)</th>
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<td>1</td>
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**Force Calibration of the Piano**

A fundamental requisite of this study was determination of the force at the tip of the pianist's index finger during piano playing. This force equals the force imparted by the finger to the piano key, which was measured indirectly through calibration of key velocity. Calibration was accomplished by playing a cylindrical piezoelectric force transducer (¾" diameter, ¾" height) on the key surface and striking it numerous times with various intensities, encompassing the range of key velocities of the piano.

Variations in style, pianistic technique, and fingertip pulp thickness were considered by using several pianists, utilizing both legato and staccato key strikes, to calibrate the piano. One female and three male subjects, with a range of piano practice history of 0 to 39 years, participated in this study (Table 1). Each subject was asked to strike the force transducer with the right index finger at two locations on each of several white keys (i.e., close to the end of the adjacent black key and near the extreme outer end of the white key). In each test the transducer was struck repeatedly, using both staccato and legato key strikes at both locations on the key, with increasing levels of acoustic intensity from "barely audible" to "as loud as possible."

**Dynamic Fingertip Force During Key Strike**

The changes in fingertip force (measured with the force transducer) occurring during the interval of fingertip/force transducer contact were analyzed for three key strikes at an acoustic volume corresponding to 96 velocity units (i.e., moderately loud). This provided information about key strike efficiency, i.e., the proportion of the total force applied to the key which was utilized for key depression.

The initial impulse imparted to the key, which determines key velocity (and thus acoustic volume), was determined for each of the three key strikes (1 staccato, 2 legato) from the "area under the curve," which was derived by integrating the fingertip/key force history.

**Modeling of Finger Forces**

A two-dimensional static index finger model was chosen to simulate the forces during a piano key strike because the majority of motion of that digit is in the sagittal plane (sagittal plane is the vertical plane which, when the hand is pronated, divides the finger into left and right halves).

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During piano play and tendon and joint forces can be solved for explicitly. In the present study these forces were determined from a free-body force analysis of each of the phalangeal segments (Fig. 1), assuming an input fingertip force of 1 unit.

The tendon moments (tendon force times perpendicular distance to the joint center), as functions of the joint flexion angles, were determined with a bow-string model. Because the paths of the tendons are guided by pulleys distal and proximal to the joint centers, flexor tendons on the palmar aspect of the joint move away from the joint centers during joint flexion (Fig. 2), decreasing the tendon tensions. Changes in key strike finger positions thus may result in large variations in tendon forces.

**Identification of Finger Positions Providing Minimum Tendon and Joint Forces**

After determining the mathematical functions relating the finger force to finger position, an optimization program (utilizing the interior penalty method of optimization) was written to select finger positions yielding minimum finger force. The forces at the metacarpophalangeal (MP) and distal interphalangeal (DIP) joints, and the tension in the flexor digitorum profundus (FDP) were chosen as the forces to be minimized. The four position variables employed were the piano key contact angle and the flexion angles at the DIP, PIP, and MP joints. The fingertip/key contact angle measured from the vertical and finger flexion angles in the program were constrained to the "normal" range of motion for each of the finger joints during piano performance. For purposes of this study, these were assumed to be 5°-85° of flexion. Wrist position was arbitrarily constrained between the range of 45° volarflexion and 45° dorsiflexion."

**RESULTS**

**Force Calibration of the Piano**

Preliminary studies testing multiple white keys indicated that the results obtained were independent of the key which was struck (upper or lower keyboard) and were independent of the location of fingertip contact on the key. Figure 3 shows the curve for fingertip load (force) versus key velocity for the four pianists using legato and staccato key strikes at two different locations on each of several keys. Variation in the force, for a given key velocity level, was large. At a velocity level of 96, for example, the minimum force was 1.7 pounds and the maximum was 4.6 pounds, i.e., 170% greater than the minimum value. Over a wide velocity range, the finger force generated by the male subject with no piano experience was about 20% higher than that for each of the three more pianistically experienced subjects.

*In volarflexion of the wrist, the hand is flexed forward or down when pronated. In dorsiflexion of the wrist the hand is "cocked" back.*
At all key velocities (i.e., acoustic volumes), legato key strikes required about 15% less force than staccato strikes.

Joint Force Optimization

The normalized DIP joint force, using two arbitrarily selected finger positions, is illustrated in Figure 4. As a result of increased flexion angles at the DIP and PIP joints and a decreased key contact angle, more than 50% reduction in DIP joint force was achieved by a change from Position 1 to Position 2.

The MP joint force as a function of MP and PIP joint flexion angles is shown in Figure 5. This three-dimensional surface represents numerous solutions to the index finger model equations throughout the range of MP flexion (5°–85°) and the range of PIP flexion (5°–85°), when the contact angle and DIP flexion angle are held constant (5° each). With this contact angle and DIP flexion angle, the minimum force on the MP joint (1.78 units) was achieved with a high MP/low PIP flexion angle. When finger posture is altered to produce a low MP/high PIP flexion angle, the MP joint force rises to 5.72 units—more than 300% of the minimum value.

Tendon Force Optimization

The FDP tendon force, as a function of DIP joint flexion angle and fingertip contact angle is shown in Figure 6. This force increases to 880% of its minimum value from a high DIP flexion angle/low contact angle posture to a low DIP/high contact angle posture. The minimum FDP tendon tension position, obtained from the optimization program, is: key contact angle = 5°, DIP flexion angle = 85°, PIP flexion angle = 5°, MP flexion angle = 59°. This minimum tendon force position is physiologically difficult to achieve and certainly not commonly used in piano playing.

FIGURE 2. Phalangeal segments and tendon pulleys (A) during joint flexion and (B) during full extension of the joint. The distance, d, between the tendon and the joint center influences the tendon force needed to support a fingertip load (see text for explanation).

FIGURE 3. Fingertip/key force versus velocity calibration data for all subjects. Staccato and legato key strikes at two sites on each of several randomly selected keys.

but Figure 6 shows clearly that reducing fingertip contact angle markedly minimized FDP tendon tension during piano playing.

Figure 6 illustrates the effect of key contact angle on the FDP tendon tension. With a 45° key contact angle (Position 1, Fig. 6), for example, FDP tendon tension is 2.6 pounds. When the contact angle is reduced to 5°, the value falls to only 0.5 pounds (Position 2, Fig. 6). However, to accomplish this decrease in key contact angle during piano playing without changing joint flexion angles would require either an increase in wrist flexion or elevation of the shoulder and elbow, neither of which may be desirable.

**Dynamic Fingertip Force During Key Strike**

Figure 7 shows fingertip force measured by the force transducer as a function of time throughout the duration of key contact at a moderately loud acoustic volume (key velocity = 96).

**Staccato.** In the staccato key strike (Fig. 7A), the first peak represents the initial impact of the finger on the key surface. The highest peak is the force on the fingertip when the key reaches its maximum displacement ("bottoms out"). The smaller, smoother peaks that follow the initial impact and "bottoming out" are due to small vibrations in the key and finger initiated by these two large impacts. When fingertip contact is broken (75 milliseconds after the initial impact and 35 milliseconds after "bottoming out"), the fingertip/key force drops to zero.

**Legato.** Figures 7B and 7C depict two randomly selected legato key strikes. In contrast to the staccato strike, little or no initial impact is generated. As in Figure 7A, the highest peaks are the forces on the fingertip immediately after the key "bottoms out."

It should be emphasized that the acoustic volume produced by each of the key strikes illustrated in Figure 7 was identical (key velocity = 96). The forces used to produce the resultant sound, however, were clearly very different. Thus, the peak fingertip forces in the two examples of legato key strike illustrated were 1.9 and 3.2 pounds, a 68% difference.

The acoustic volume of a given note is a direct result of the summation of fingertip forces on the key from the time of initial contact to "bottoming out." This is confirmed in Figure 7 in which the summation of forces in 3 different key strikes, which produced identical acoustic volume, were identical, i.e., the area under each fingertip/key force curve from the time of initial impact to the time of "bottoming out" was approximately 25 pound/milliseconds.

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**Greater piano proficiency should lead to more effortless and efficient key strikes.**

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FIGURE 5. MP joint force (assuming a fingertip force of 1.0 units) as a function of both MP joint flexion angle and PIP joint flexion angle. If the magnitude of the fingertip force is greater or less than 1, actual MP joint force may be obtained by multiplying the joint force in the figure by the magnitude of the fingertip force. Positions 1 and 2 have contact and DIP flexion angles of 5°. However, the PIP and MP flexion angles for Position 1 are 30° and 5°, whereas those for Position 2 are 5° and 85°. Position 2 is the minimum MP joint force position. The MP force magnitude is 3.75 pounds (assuming a fingertip force of 1 pound) at Position 1, but only about one-half as great, 1.78 pounds, at Position 2.
DISCUSSION

The greater key force utilized by the subject with no piano experience, in comparison with that used by the other subjects, might have been expected because greater piano proficiency should lead to more effortless and efficient key strike. The decreased force required in legato key strikes may be due to better muscular control throughout the strike and thus greater efficiency than with a staccato key strike. More data from additional subjects are required to substantiate these results.

Even though few, relatively small, deviations from the force versus key velocity values were noted in relation to type of key strike (staccato or legato) or piano experience of the subject, the scatter of data in Figure 3 is surprising. The large variation in key force magnitude at a given key velocity (loudness) suggests that improvements in playing technique could decrease the fingertip force on the key to levels near or even below the lowest calibration points shown in Figure 3.

Some insight into the problem of reducing finger force at a given acoustic volume can be gained from the key force versus time plots (Fig. 7). Although the two legato key strikes selected for analysis produced the same acoustic volume (key velocity = 96 for both), maximum fingertip forces were markedly different. The legato key strike illustrated in Figure 7C is much less efficient than the legato strike in Figure 7B, since the greater maximum fingertip force had no effect on the sound output of the piano.

Theoretically, the large peak produced after the “bottoming out” of the piano key could be eliminated if the pianist accelerated the key during its downward motion and released his finger immediately before the key reached the end of its travel. Because the fingertip force imparted to the key immediately following “bottoming out” makes no contribution to the sound produced, optimal pianistic technique to minimize finger joint and tendon forces would release the finger from the key prior to “bottoming out” impact.

FIGURE 6. FDP tendon tension (assuming a unit fingertip force) as a function of contact angle and DIP joint flexion angle. Positions 1 and 2 have DIP and PIP flexion angles of 5° and an MP flexion angle of 59°. However, the contact angle for Position 1 is 45° and that for Position 2 is 5°.

FIGURE 7. Fingertip force throughout the interval of fingertip key contact during staccato and legato key strikes at constant acoustic volume (96 units). (A) = Staccato strike. (B) and (C) = Legato strikes.
Pianists incur more injuries of the fourth and fifth fingers because these fingers are required to produce the same acoustic intensity as the larger digits, but have the smallest joint contact areas and thus the highest joint stresses.

The possibility of dramatically reducing joint force by modifying finger position in piano playing is illustrated in Figure 4 by the more than 50% reduction in DIP joint force from Position 1 to Position 2. The force at the DIP joint is directly related to the impact stress imparted to the joint cartilage. A 50% reduction in stress at this joint is highly significant because the stress level (joint force divided by contact area) is frequently higher at the DIP joint than that at either the PIP or MP joints. This may help to explain why pianists incur more injuries of the fourth and fifth fingers than of the other fingers—these fingers are required to produce the same acoustic intensity as the larger digits, but have the smallest joint contact areas and thus the highest joint stresses.

The nearly vertical optimal finger position suggested by the MP joint force and FDP tendon tension optimizations (Figs. 5 and 6) is not commonly utilized by pianists, yet it may provide valuable information if analyzed more closely. The large MP flexion angle increases the moment arms of the flexor tendons, such as the FDP, greatly reducing their tensions and the joint force for a given load. Also, as PIP flexion angle, and thus fingertip moment about the MP joint (finger force times perpendicular distance to MP joint center), increases, the flexor tendon tensions must increase to balance the greater moment thus increasing the joint force.

When tendon tensions and joint forces are decreased by optimization of finger positions as described above, corresponding increases in forces and tensions are not necessarily seen elsewhere in the finger. Thus, minimizing the tension in one tendon usually reduces tensions in other tendons and forces in related joints.

Clinical Application

The optimization program written for this analysis is sufficiently general to minimize any tendon tension, joint force, joint stress, or combination of these, with the application of user-defined anatomically and physiologically appropriate constraints (e.g., wrist position, joint flexion angles). Minimizing tendon tension may be useful in alleviating tendinitis and other musculoskeletal problems. For example, the extrinsic finger flexor tendons pass through the carpal tunnel in the wrist and attach proximally to the forearm muscles. Unnecessarily high forces in these tendons due to suboptimal finger position, in combination with a relatively high degree of volar or dorsiflexion of the wrist, could produce swelling and result in median nerve compression and carpal tunnel syndrome.

When a musician reports pain in the volar aspect of the upper extremity, he may be diagnosed by a physician as having tendinitis, due to “overuse.” Treatment in such cases typically consists of an anti-inflammatory medication and greatly restricted practice schedule. Professional musicians, who commonly experience such performance-related pain, rely heavily on exhaustive practice regimens to “stay on top” in terms of performance. The optimization analysis technique presented herein can be used to provide data on finger postures that minimize forces in digital tendons and joints during piano playing. With such information, the musician/patient could utilize the suggested optimal position or, at least, work toward it to reduce tension in the involved tendon. Alternatively, the finger positions utilized by the musician during piano playing could be determined with stop-action video and the data could then be entered into the finger-force modeling program to determine tendon tension magnitudes.

The data available from these optimization techniques may be of interest to teachers of piano technique as well as to health professionals. Obviously, this approach could be useful also for wind and string players with similar performance-related musculoskeletal problems, assembly line workers, and others in hand-intensive jobs requiring fingertip pinch tasks.

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REFERENCES