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FINGER JOINT FORCE MINIMIZATION IN PIANISTS USING OPTIMIZATION TECHNIQUES

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Abstract—A numerical optimization procedure was used to determine finger positions that minimize and maximize finger tendon and joint force objective functions during piano play. A biomechanical finger model for sagittal plane motion, based on finger anatomy, was used to investigate finger tendon tensions and joint reaction forces for finger positions used in playing the piano. For commonly used piano key strike positions, flexor and intrinsic muscle tendon tensions ranged from 0.7 to 3.2 times the fingertip key strike force, while resultant inter-joint compressive forces ranged from 2 to 7 times the magnitude of the fingertip force. In general, use of a curved finger position, with a large metacarpophalangeal joint flexion angle and a small proximal interphalangeal joint flexion angle, reduces flexor tendon tension and resultant finger joint force.

NOMENCLATURE

MP	metacarpophalangeal
PIP	proximal interphalangeal
DIP	distal interphalangeal
FDP	flexor digitorum profundus tendon tension
FDS	flexor digitorum sublimis tendon tension
INT	intrinsic muscle tension
RI	radial interosseous muscle tension
UI	ulnar interosseous muscle tension
LU	lumbrical muscle tension
TE	terminal extensor tendon tension
ES	extensor slip tendon tension
RB	radial band muscle tension
UB	ulnar band muscle tension
F_{DIP}	DIP joint reaction force
F_{PIP}	PIP joint reaction force
F_{MP}	MP joint reaction force
θ_0	key contact angle (with respect to vertical)
θ_1	DIP joint flexion angle
θ_2	PIP joint flexion angle
θ_3	MP joint flexion angle
β	sum of finger position angles
L_1	distal phalanx length
L_2	middle phalanx length
L_3	proximal phalanx length
d	tendon moment arm length
F	force
F_x, F_y	components of force in X and Y directions
M	moment
P, F_{key}	fingertip/key force
a_{tip}	acceleration of fingertip
$a_{i,j}$	tendon tension matrix coefficient
b_i	matrix coefficient
θ_i	finger position variable
g_i	inequality constraint
f	objective function

INTRODUCTION

Musculoskeletal problems resulting in pain and loss of dexterity often plague serious pianists. The more common complaints are due to tendonitis, bursitis and carpal tunnel syndrome, all of which are commonly generalized as 'overuse syndromes' (Caldron *et al.*, 1986; Hiner *et al.*, 1987; Knishkowy and Lederman, 1986). Understanding how the performance mechanics of piano playing affect forces in the joints, tendons, ligaments, and muscles may provide insight into the causes of these conditions and offer methods for minimizing their effects.

Several two- and three-dimensional models have been developed (An *et al.*, 1979, 1984; Smith, 1974; Weightman and Amis, 1982) that quantitatively describe the open or closed kinematic chain interphalangeal forces in the finger. The magnitudes of these forces during piano key strike activities depend upon anatomy and finger posture. Sagittal plane finger position variables affecting tendon and joint forces during piano performance include the fingertip/key contact angle, flexion angles of the distal interphalangeal (DIP), proximal interphalangeal (PIP) and the metacarpophalangeal (MP) joints, and the fingertip force on the key (Weightman and Amis, 1982).

The objectives of this study were to develop an analytical model for determining tendon and joint forces during piano playing and to use this model to determine finger positions that reduce these forces. These methods could aid in diagnosing conditions that lead to overuse syndromes and possibly to suggest mechanically optimal playing techniques. Accordingly, a two-dimensional finger model was used to determine the joint reaction forces and tendon tension forces for different finger postures during piano playing. A numerical optimization routine was developed to determine the finger postures that minimize selected joint forces, tendon forces and combinations thereof. Using experimental motion measurements, the influence of finger inertial forces during piano playing was determined.

MATERIALS AND METHODS

The force imparted to the key during key strike is the sum of that due to active muscle action and that

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due to inertial force from decelerating the finger mass. A comparison of the inertia force to total key strike force indicates that portion of the force due to active muscle action and that due to finger inertia. A worst-case condition was considered by assuming a straight finger pivoting at the MP joint with the key force at the fingertip. The finger mass moment of inertia, i_{mp}, about the MP joint was approximated by assuming the finger to be a conical segment with a specific density of 2.0.

Summing moments about the MP joint, setting this equal to i_{mp} times the angular deceleration and then solving, gives the key strike force due to the inertia of the finger, i.e.

$$F_{i,\text{key}} = \frac{i_{mp}\, a_{\text{fingertip}}}{(L_1 + L_2 + L_3)^2}, \tag{1}$$

where F_{key} is the maximum inertia force on the key, i_{mp} is the mass moment of inertia of the finger, $a_{\text{finger-tip}}$ is the maximum deceleration of the fingertip at the key strike and L_{1-3} are the finger segment lengths.

The acceleration of the right index finger for two subjects was measured with a WATSMART spatial motion analysis system during rapid trilling motion, where inertial forces could be large due to high-speed finger movement. This motion was selected because two or more fingers move in rapid succession within the sagittal plane, while the hand and forearm remain relatively motionless. The resulting finger key strike force is due primarily to the active muscle and finger inertia forces. The WATSMART system uses infrared position detectors to record the position of infrared light–emitting diodes (IREDS) attached to the finger segments, from which system software determines position, velocity and acceleration. Four IREDS were attached with medical adhesive to the skin of the radial side of each subject's right index finger at the MP, PIP and DIP joints and very near the fingertip. A fifth IRED, mounted on the piano key, indicated when key strike occurred. The key contact force was measured indirectly through the piano's digital interface (Harding *et al.*, 1989).

Data were recorded for a trilling motion, at a rate of approximately 2.5 key strikes per second, and approximately equal acoustic volumes (key contact forces) from each of the subjects. Position data for each IRED was recorded at a sampling rate of 400 Hz (and filtered with a 10 Hz low-pass filter to provide smooth acceleration data) for 10 s, during which each subject was asked to begin with a moderately rapid trill of moderate dynamic volume and then to increase the speed to 'as fast as possible' near the end of the time period. Raw data was then converted to three-dimensional coordinates, verified, filtered and plotted. Data acquisition errors with the WATSMART system due to reflections were minimized through the use of anti-reflective coverings on piano keys and adjacent surfaces. The resultant spatial accuracy calibrations were typically about 1.5 mm. The maximum decelerations at key strike were used to determine the maximum value of that portion of the key strike force due to finger inertia.

To investigate optimal finger positions for piano play, a force model of the index finger similar to that of Weightman and Amis (1982) was developed to determine the forces in the tendons and joints of the finger as a function of applied fingertip force and anatomic finger position during key strike. Since the finger inertia forces were found to be negligible (see Results), a quasi-static model was developed. It was assumed that the phalangeal segments were rigid bodies and that motion was two-dimensional and in the sagittal plane. Since the finger joints are synovial joints, the IP and MP joints were assumed to be frictionless. Since both the IP and MP joints have relatively fixed centers of rotation, pin joints were assumed. Tendons were assumed to be tight at the time of key impact due to the small inertial force required to accelerate the finger toward the key. Also, joint and fingertip/pulp damping were assumed to be negligible because of the relatively high rate of fingertip/key force application.

Based on the physiology and anatomy of the finger, the tendons and intrinsic muscles required to balance the fingertip/key force (assumed to be applied normal to the fingertip contact surface) are shown in Fig. 1. The long extensor tendon is needed only to raise or extend the finger and can thus be neglected in piano key strike actions. Palpation of the dorsiflexed wrist during exertion of maximum force at key strike shows this to be true. From anatomic observations by Landsmeer (1963), Smith (1974), and Chao and An (1978a), the intrinsic muscle forces and tendon ten-

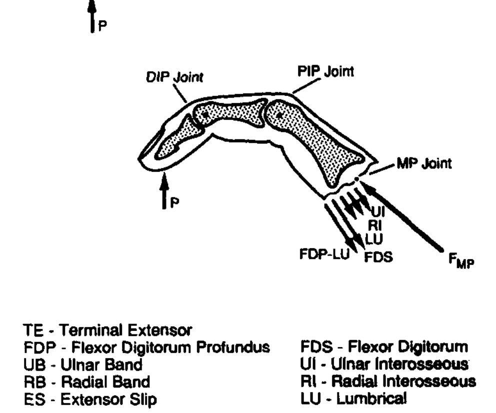

Fig. 1. Phalangeal segments in equilibrium. Tendon tensions and joint reaction forces determined by summing moments and then forces about each joint and free body, respectively.

sions shown in Fig. 1 were assumed to divide as follows:

$$\mathrm{TE} = \mathrm{RB}+\mathrm{UB} = \tfrac{2}{3}\mathrm{LU}+\tfrac{1}{3}\mathrm{UI}, \tag{2}$$

$$\mathrm{ES}=\tfrac{1}{3}\mathrm{RI}+\tfrac{1}{3}\mathrm{UI}+\tfrac{1}{3}\mathrm{LU}, \tag{3}$$

$$\mathrm{UB}=\tfrac{1}{3}\mathrm{UI}, \tag{4}$$

$$\mathrm{RB}=\tfrac{2}{3}\mathrm{LU}. \tag{5}$$

Tensions developed in the intrinsic muscles, RI, UI and LU, were assumed to be proportional to the physiological cross-sectional area (PCSA) of the muscles as reported by Chao and An (1978a):

$$\mathrm{RI} = 0.686\ \mathrm{INT}, \tag{6}$$

$$\mathrm{UI} = 0.23\ \mathrm{INT}, \tag{7}$$

$$\mathrm{LU} = 0.083\ \mathrm{INT} \tag{8}$$

and

$$\mathrm{INT} = \mathrm{RI}+\mathrm{UI}+\mathrm{LU}. \tag{9}$$

The four angular finger segment positions, θ_i, that describe the finger posture at key strike are the key contact angle and the DIP, PIP and MP flexion angles, as shown in Fig. 2. The wrist and forearm positions were determined indirectly by specifying these four angles, since piano bench height is typically adjusted to position the elbow slightly above the level of the keyboard.

Tendon moment arms and angles between the tendons and the more distal phalanges, including the effect of the 'tendon pulleys' at each joint, were calculated by the model for each finger configuration, using the sagittal plane coordinates from the normative model for the hand developed by An *et al.* (1979).

The bow-string model was used to determine the nonlinear relationship between the tendon and intrinsic muscle moment arms and the joint flexion angles. 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 flexion (Fig. 3), decreasing the tendon tensions required to balance a given fingertip load. Tendons dorsal to the joint move closer to the joint center, decreasing their mechanical advantage. Tendon and intrinsic muscle moment arms were normalized with respect to the distance between the center of rotation of the DIP joint and the center of the concave surface of the PIP joint.

As the fingertip contact angle (with respect to vertical) increases, the contact point between the key and the finger moves proximally. Although the actual distal phalangeal segment length is fixed, the 'effective' length used to calculate fingertip force moments about various joints can change with fingertip contact angle. The relationship between key contact angle and effective distal phalanx length, L_1, based on the anatomy and the geometry of fingertip/key contact, was expressed as:

$$L_1 = 15+9.9(\cos^2\theta_0)\ \mathrm{mm}. \tag{10}$$

The quasi-static key strike assumption provides nine equations of equilibrium (Newton's second law, neglecting inertial terms), namely, balancing the moments and forces at each of the three finger joints (Fig. 1). Summing moments about the center of rotation of each of the joints (DIP, PIP and MP) gives:

$$(\mathrm{FDP}-\mathrm{LU})(d_2)-\mathrm{TE}(d_1)-P(L_1\sin\theta_0)=0, \tag{11}$$

$$(\mathrm{FDS})(d_6)+(\mathrm{FDP}-\mathrm{LU})(d_3)-\mathrm{ES}(d_7)-\mathrm{RB}(d_4)$$
$$-\mathrm{UB}(d_5)-P[L_1\sin\theta_0+L_2\sin(\theta_0+\theta_1)]=0, \tag{12}$$

$$\mathrm{FDS}(d_9)+(\mathrm{FDP}-\mathrm{LU})(d_8)+\mathrm{LU}(d_{11})+\mathrm{RI}(d_{10})$$
$$+\mathrm{UI}(d_{12})-P[L_1\sin\theta_0+L_2\sin(\theta_0+\theta_1)$$
$$+L_3\sin(\theta_0+\theta_1+\theta_2)]=0, \tag{13}$$

where d_j is the tendon moment arm of tendon j, θ_i is the flexion angle of joint 1,2 or 3 (DIP, PIP or MP) and P is the fingertip force. It should be noted that this relatively simple model has a shortcoming common to other statically determinate models. The FDP tendon flexes the inter-phalangeal joints and extends the DIP and PIP joints (through the lumbrical, LU). LU tension was assumed to decrease equally the tension in the FDP tendon, which may not be precisely true since FDP and LU muscle length changes during activation do not occur in a parallel fashion. Any error is likely small, however, since LU tension is always relatively low.

Combining equations (2)–(8) with equations (11)–(13) yields the following matrix:

$$a_{11}(\mathrm{INT})+a_{12}(\mathrm{FDP})+a_{13}(\mathrm{FDS})=b_1,$$
$$a_{21}(\mathrm{INT})+a_{22}(\mathrm{FDP})+a_{23}(\mathrm{FDS})=b_2,$$
$$a_{31}(\mathrm{INT})+a_{32}(\mathrm{FDP})+a_{33}(\mathrm{FDS})=b_3, \tag{14}$$

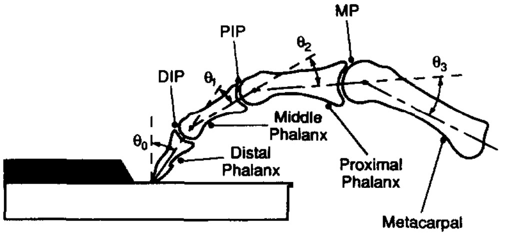

Fig. 2. Finger position variables, θ_i. Key contact, DIP flexion, PIP flexion, and MP flexion angles.

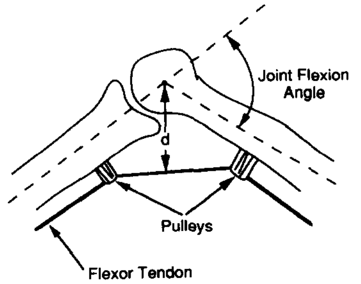

Fig. 3. Tendon bow-string model. Tendon moment arm increases as joint flexes.

where a_{mn} are functions of d_j and b_m are functions of L_i, θ_i and P.

Assuming a unit fingertip key force, P, the tensions in the tendons and intrinsic muscles (normalized in terms of the input force, P) were determined by solving equation (14) and then equations (2)–(8).

The reaction forces at the articulating surfaces of the joints were determined by balancing forces in the vertical and horizontal directions for each of the phalangeal segments shown in Fig. 1, assuming that each joint reaction force passes through the joint's center of rotation. For the three free-body segments,

$$\sum F_x = 0,$$
$$\sum F_y = 0, \tag{15}$$

where tendon and intrinsic muscle directions were determined from the slope of the line through the distal and proximal pulleys outlined previously and the fingertip force was transformed back to the joint coordinate frame.

The shear components of the joint forces increase as the joints flex and, for some finger positions, the model may predict joint reaction forces acting at, or outside, the edge of the articular contact of the joint. For this condition, the MP joint relies on ligamentous support to prevent palmar subluxation, whereas dorsal subluxation is impossible due to the volar plate. The support provided by the collateral ligaments at the DIP, PIP and MP joints has been included in the model. Based on the physiology of the collateral ligament, it was assumed that the lines of action of the ligaments pass through the joint's center of rotation at a fixed angle of 45° to the axis of the more distal phalanx, originating from a dorsal position on the more proximal head and inserting on the volar lip of the concave, more distal, phalangeal base. Tension in the ligaments decreases the volar shear component and stabilizes the joint, but does not affect tendon tensions, since the ligament moment arms are zero (or at least much smaller than those of the tendons).

Ligaments restrict the resultant joint force angle to not less than 160°, keeping the resultant force within the concavity of articulation. The magnitude of the new joint reaction force then acts at an angle of 160°, and increases in magnitude by no more than 10%.

EMG studies have shown (and other models predict) that the intrinsic finger muscles are not always needed to balance a fingertip load (Tubiana, 1981). Indeed for certain finger positions, the present model predicts a zero-tension condition in the intrinsics and sometimes in the FDS or FDP. This was incorporated in the computer model by checking the sign of each tendon or intrinsic force (FDP, FDS or INT) after an initial solution of equation (14). If a force is negative, it is set to zero and the remaining equations are solved.

Average stresses for the DIP, PIP and MP joints were approximated by dividing the force by the joint area. This gives an average stress over the contact area for each joint for each finger position considered. The articulating joint contact areas for the DIP, PIP and MP joints used in determining the joint stresses were those measured by Moran et al. (1985). However, he indicated that other investigators had observed smaller areas than he measured, therefore, actual stresses could be greater than those determined in this study.

A numerical optimization program was developed that incorporates the above finger model as a subroutine. The objective function to be minimized can be any of the tendon, intrinsic muscle or resultant joint forces that are combinations of linear and nonlinear functions from the finger force model. In some of these functions, such as intrinsic muscle force distribution, the finger-position-dependent moment arm lengths may be considered to be linear with nonlinear equality constraints, that are taken into account in the evaluation of the objective function.

The design variables in the finger force optimization are the key contact angle, θ_0, and finger joint flexion angles, θ_1, θ_2, and θ_3. Physiologically, finger joint flexion angles larger than 85° are not readily attainable. Also, flexion angles less than 5° induce additional moment constraints on the joints from ligamentous structures. Therefore, each joint flexion angle was constrained to be within these limits (between 5 and 85°). The key contact angle was constrained within these limits as well, since pianists normally confine their playing within the range of nearly vertical tip contact to nearly horizontal pulp contact. These inequality constraints can be expressed as follows:

$$5° \leqslant \theta_i \leqslant 85°, \quad i = 0, 1, 2, 3 \tag{16}$$

or

$$\sin\theta_i \cos\theta_i \leqslant 0.0868, \quad i = 0, 1, 2, 3. \tag{17}$$

The normalized inequality constraint thus becomes

$$g_j(\boldsymbol{\theta}) = \frac{0.0868 - \sin\theta_i \cos\theta_i}{0.0868}, \quad j = 1, 4. \tag{18}$$

The constraints of equation (18) have been normalized to increase the convergence rate. Additional constraints were needed to keep θ_i within the first quadrant, i.e.

$$g_k(\boldsymbol{\theta}) = \frac{\theta_i - 85°}{85°}, \quad k = 5, 8. \tag{19}$$

Finally, during piano playing, the sum of the three joint flexion angles and tip contact angle were constrained by the wrist position to be between 45° volar flexion and 45° dorsal flexion, i.e.

$$45° \leqslant \sum_0^3 \theta_i \leqslant 135°, \tag{20}$$

which is simplified as

$$\sin^2\beta \geqslant 0.5 \tag{21}$$

or

$$g_{(9)}(\boldsymbol{\theta}) = \frac{0.5 - \sin^2\beta}{0.5}, \tag{22}$$

where

$$\beta = \sum_{0}^{3} \theta_i \tag{23}$$

and, keeping the playing position within the 1st and 4th quadrants of the sagittal plane,

$$g_{10}(\boldsymbol{\theta}) = \frac{\beta - 135^\circ}{135^\circ}. \tag{24}$$

The optimization problem is then to minimize the objective function, $f(\boldsymbol{\theta})$, where

$$f(\boldsymbol{\theta}) = F_{MP}, F_{PIP}, F_{DIP}, \mathrm{FDS}, \mathrm{FDP}, \mathrm{INT}, \mathrm{LU}, \mathrm{TE}, \mathrm{RB}, \mathrm{UB}, \mathrm{RI}, \mathrm{UI}, \text{etc.} \tag{25}$$

(or any combination thereof)

so that

$$g_j(\boldsymbol{\theta}) \leqslant 0, \quad j = 1, 10. \tag{26}$$

An optimization program using the nonlinear interior penalty function method and Davidson–Fletcher–Powell (DFP) variable metric method (Rao, 1984) was written to minimize the objective function(s) with the given constraints. The nonlinearity of the objective function dictates the use of nonlinear programming methods. Objective function minimization results were verified to be global minimums by using different initial finger positions as 'starting points' within the objective space.

RESULTS

The maximum finger deceleration and acceleration measured with the WATSMART system for the three subjects were 3.5 and 3.3 g, respectively, which were recorded during a trilling motion at 2.5 key strikes per second and a maximum key strike force of 8.9 N. The maximum deceleration occurred as the key reached the end of its stroke and the maximum acceleration occurred at the beginning of the downward motion of the finger. The maximum inertia force imparted to the key is the finger mass moment of inertia times the maximum deceleration divided by the finger length squared, which was 0.23 N; only 2.6% of the maximum key strike force.

The results of the finger model show the dramatic joint force reductions that are possible with small variations in finger key strike position (see Fig. 4). The DIP joint force, for example, can be greatly reduced by minimizing key contact angle (thus minimizing the finger force moment about the DIP joint) while maintaining some degree of DIP joint flexion to increase the FDP tendon moment arm about that joint.

Normalized tendon tensions and joint forces for five different finger key strike positions exemplify the dramatic differences in tendon and joint forces, as well as joint stresses (see Fig. 5 and items 1–5 in Table 1). The key strike finger positions generally increase from an extended finger position with a large key contact angle to a more curved position with a smaller key contact angle. Joint forces typically increase from distal to proximal in the digit due to increasing moment of the key contact force about the more proximal joint. The magnitudes of all tendon and joint forces generally decrease with increasing MP joint

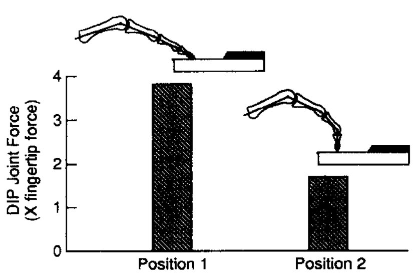

Fig. 4. Normalized DIP joint force for two typical piano key strike finger positions.

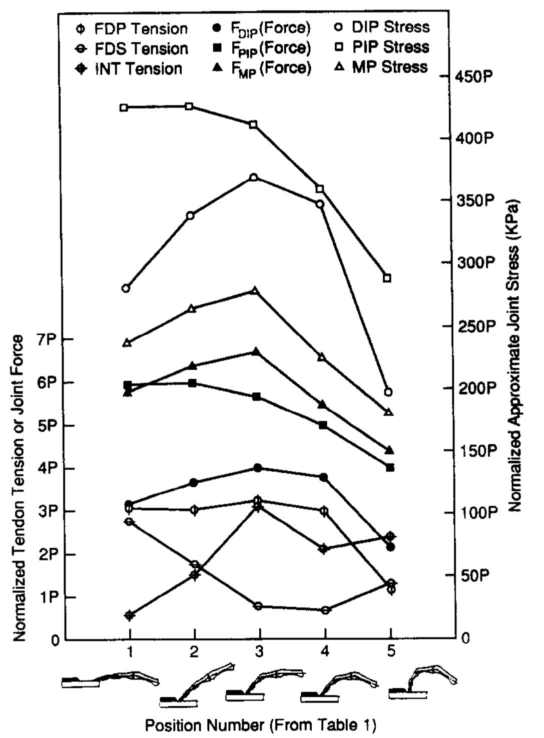

Fig. 5. Normalized finger tendon forces, joint forces and joint stresses for five common finger postures varying from straight to increasingly curved. These data are also listed in Table 1. ('P' equals fingertip or key strike force.) Forces and stresses generally decrease with increasing finger curvature.

Table 1. Normalized resultant joint forces and tendon tensions for various finger positions

No.	Objective function minimized	Position $\theta_0, \theta_1, \theta_2, \theta_3$ (degrees)	Normalized forces (× fingertip/key force): Joint reaction forces F_{DIP}	F_{PIP}	F_{MP}	Tendon tensions: INT	FDP	FDS	UI	RI	LU	RB	UB	ES	TE
1	—	80, 5, 5, 20	3.07	5.88	5.72	0.49	2.97	2.65	0.11	0.34	0.04	0.03	0.04	0.16	0.06
2	—	45, 5, 10, 5	3.70	5.93	6.41	1.52	3.02	1.74	0.35	1.05	0.13	0.08	0.12	0.51	0.20
3	—	40, 5, 35, 10	4.04	5.72	6.73	3.17	3.23	0.77	0.73	2.17	0.26	0.18	0.24	1.06	0.42
4	—	40, 5, 35, 35	3.78	5.01	5.46	2.13	3.01	0.67	0.49	1.46	0.18	0.12	0.16	0.71	0.28
5	—	10, 25, 50, 40	2.16	4.00	4.40	2.42	1.15	1.31	0.56	1.66	0.20	0.13	0.19	0.81	0.32
6	F_{DIP}	5, 85, 5, 40	1.00	4.42	4.03	0.16	0.34	4.00	0.04	0.11	0.01	0.01	0.01	0.05	0.02
7	F_{PIP}	5, 5, 5, 56	1.44	2.03	1.87	0.19	0.45	0.53	0.04	0.13	0.02	0.01	0.01	0.06	0.02
8	F_{MP}	5, 5, 5, 65	1.44	2.02	1.78	0.17	0.45	0.53	0.04	0.12	0.01	0.01	0.01	0.06	0.02
9	FDP	5, 85, 5, 59	0.98	4.31	3.91	0.03	0.33	3.96	0.01	0.02	0.00	0.00	0.00	0.01	0.00
10	FDS	24, 6, 69, 17	3.64	4.69	5.67	3.93	2.62	0.00	0.90	2.70	0.33	0.22	0.30	1.31	0.52
11	INT	35, 29, 6, 51	2.55	5.20	4.80	0.00	1.99	2.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	$1/F_{DIP}$	47, 5, 59, 5	4.41	5.74	7.09	4.23	3.63	0.24	0.97	2.90	0.35	0.23	0.32	1.41	0.56
13	$1/F_{PIP}$	58, 16, 6, 5	3.21	6.39	6.64	1.07	2.84	2.90	0.25	0.73	0.09	0.06	0.08	0.36	0.14
14	$1/F_{MP}$	49, 5, 38, 5	4.25	6.13	7.35	3.59	3.54	0.86	0.83	2.47	0.30	0.20	0.28	1.20	0.48
15	1/FDP	56, 5, 56, 5	4.31	5.72	6.93	3.85	3.68	0.45	0.89	2.65	0.32	0.21	0.30	1.28	0.51
16	1/FDS	5, 82, 5, 5	1.15	5.13	5.33	0.96	0.45	4.25	0.22	0.66	0.08	0.05	0.07	0.32	0.13
17	1/INT	8, 6, 80, 5	2.89	4.36	5.84	4.97	1.69	0.00	1.14	3.41	0.41	0.28	0.38	1.66	0.66
18	$F_{DIP}+F_{PIP}+F_{MP}$	5, 5, 5, 85	1.44	2.02	1.78	0.16	0.45	0.52	0.04	0.11	0.01	0.01	0.01	0.05	0.02
19	FDS+FDP+INT	5, 5, 5, 85	1.44	2.02	1.78	0.16	0.45	0.52	0.04	0.11	0.01	0.01	0.01	0.05	0.02

flexion angle and decreasing key contact angle. Increasing the PIP flexion angle (Fig. 5, positions 2 and 3) increases all finger joint and tendon forces except the FDS tendon tension and the PIP force. This phenomenon is contrary to the trends at DIP and MP joints due to the fact that a number of INT tendons are located dorsal to the joint center and thus have their mechanical advantages decreased by increasing PIP joint flexion. Although joint forces tend to increase proximally for a given finger key strike position, stresses are greatest at the DIP and PIP joints since contact areas decrease in more distal finger joints.

A wide variety of 'optimal' finger positions resulted from minimizing the following objective functions: (1) the reaction forces at the DIP, PIP and MP joints, (2) tensions in the FDP, FDS and INT tendons and muscles, (3) the sum of the joint reaction forces and (4) the sum of tendon tensions. The objective function and the corresponding finger position and joint and tendon forces that minimize (or maximize) the objective function are presented in Table 1 and Figs 6 and 7. Minimizing the reciprocal of a quantity gives the finger position that maximizes that quantity. Finger positions for both minimum and maximum joint and tendon forces generally occur where moments about the joints that these tendons flex are minimized or maximized, respectively.

Each objective surface is a five-dimensional (four design or position variables) hypersurface that cannot be easily represented. The MP joint force as a function

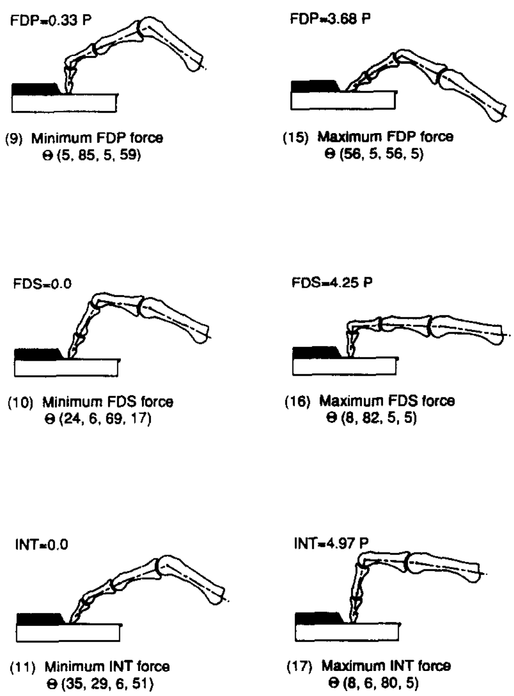

Fig. 7. Minimum and maximum tendon forces and corresponding finger postures resulting from numerical optimizations. Complete force data for each position are given in Table 1. Forces generally decrease as the fingertip force moment arm is decreased and tendon moment arms are increased.

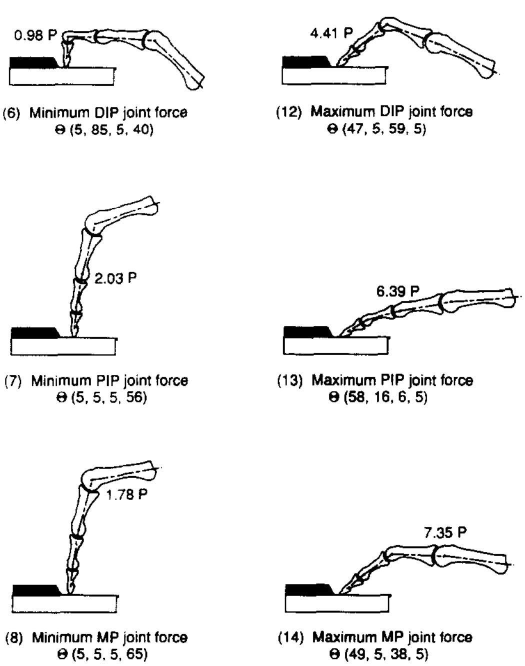

Fig. 6. Minimum and maximum joint forces and corresponding finger postures resulting from numerical optimizations. Complete force data for each position are given in Table 1. Forces generally decrease as the fingertip force moment arm is decreased and tendon moment arms are increased.

of the MP and PIP joint flexion angles, provides objective function sensitivities to these finger position variables (Fig. 8). This three-dimensional surface represents numerous solutions of the finger model throughout the range of PIP and MP flexion (5–85°), while the contact angle and DIP flexion angle are each constant at 5°. With this contact angle and DIP flexion angle, the minimum force on the MP joint (1.78 units) was achieved with a high MP and low PIP flexion angle. When finger posture is altered to produce a low MP and high PIP flexion angle, the MP joint force rises to 5.72 units—more than 3 times the minimum value.

The FDP tendon force increases to 8.8 times the minimum value as finger position changes from a high DIP flexion angle and low contact angle to a low DIP and high key contact angle (see Fig. 9). 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° (Fig. 7, position 9). This minimum tendon force position is physiologically difficult to achieve and certainly not commonly used in piano playing, but Fig. 9 shows clearly that reducing fingertip contact angle markedly decreases FDP tendon tension during piano playing. With a 45° key contact angle, for example, normalized FDP tendon tension is 11.56. When the contact angle is reduced to 5°, the value is

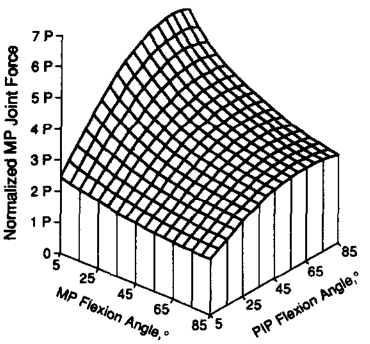

Fig. 8. MP joint force as a function of MP and PIP joint flexion angles. Key contact angle, $\theta_0 = 5°$, DIP flexion angle, $\theta_1 = 5°$. Increasing the key contact angle significantly increases the moments at each of the joints due to the finger tip forces resulting in increases in the tendon tensions.

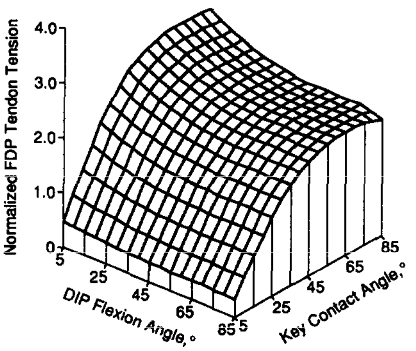

Fig. 9. FDP tendon tension as a function of DIP flexion and key contact angles. PIP flexion angle, $\theta_2 = 5°$; MP flexion angle, $\theta_3 = 5°$. Increasing the key contact angle significantly increases the moments at each of the joints thereby increasing the tendon tensions.

decreased to 2.22. 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. Similar objective surfaces as those shown in Figs 8 and 9 were observed for the other objective functions.

DISCUSSION

A biomechanical finger mode for sagittal plane motion, integrated with a numerical optimization routine, has been developed to determine finger positions which minimize tendon and joint forces during piano performance. The use of a quasi-static finger model to determine tendon and interjoint forces is justified by the fact that finger inertia forces acting on the key are less than 3% of the active muscle forces during piano key strike. Its two-dimensional derivation is well suited for most piano performance finger force predictions since key strike activities occur primarily within the sagittal plane. Conversely, the model does not accurately predict finger forces during out-of-plane or three-dimensional loadings associated with radial or ulnar rotations of the hand which invoke asymmetric intrinsic tendon forces and ligamentous support.

Similarly to previously developed finger models, tensions developed in the intrinsic muscles were assumed to be proportional to the PCSA of each muscle. However, electromyographic studies of larger muscle groups have shown that adaptation occurs between muscles throughout repetitive activation, presumably due to fatigue. Although this phenomenon likely occurs during piano playing as well, quantifying the adaptions without 'instrumenting' a pianist would be difficult at best; therefore, the inherent inaccuracies of a PCSA-based model must be accepted.

Other two- and three-dimensional finger force models have predicted similar tendon and inter-joint forces to the present model (see Table 2). Note that the forces obtained by Chao and An (1978b) (average of 8 solutions) were generally much higher than those predicted by other models because of the inclusion of the passive long extensor tendon tension. The slight differences between the forces determined by Weightman and Amis (1982) and those obtained in this study are due to the additional collateral ligament constraints for the IP joints and a different method of calculating the effective distal phalangeal length as a function of key contact angle in the present model.

The results of applying numerical optimization to the finger model clearly delineate minimum and maximum tendon and joint force positions for piano performance. Unfortunately, minimum joint force positions are often unrealistic for piano play but maximum joint force positions are more commonly used (Fig. 6). Investigating the biomechanical causes of these force differences may thus elucidate new positions individual pianists can use to reduce pain and occurrence of injury.

A number of interesting comparisons of joint and tendon forces can be made with the finger model results shown in Fig. 5. In general, the MP joint force is greater than the PIP joint force which, in turn, is greater than the DIP joint force, because the moment of the fingertip force about the respective joints progressively increases. Since the joint contact areas also increase from DIP to PIP to MP joint, the joint stresses are higher for the PIP and DIP joints than for the MP joint. This may help explain why pianists incur more injuries in the fourth and fifth fingers than in other digits, since these fingers are required to produce the same acoustic intensity as the larger digits, but have smaller joint contact areas and thus incur higher joint stresses. The FDP tendon is the primary flexor tendon and its tension generally follows the trend of the joint forces for the different positions.

In Fig. 5, the INT muscle tensions and DIP and MP joint forces increase slightly from position 1 to 2

Table 2. Comparison of published results with those from present model, for similar finger postures

Paper	Position $\theta_0, \theta_1, \theta_2, \theta_3$ (degrees)	Normalized forces ($\times$ fingertip/key force) Joint reaction forces F_{DIP}	F_{PIP}	F_{MP}	Tendon tensions INT	FDP	FDS
Present model	45, 25, 50, 48	3.1	4.5	4.7	1.5	2.6	1.3
Weightman and Amis (1982)	45, 25, 50, 48	2.8	4.3	4.2	1.5	2.2	1.5
Chao and An (1978a)	45, 25, 50, 48	—	—	—	4.1	4.0	0.8
Present model	40, 30, 40, 10	3.2	5.6	6.3	2.7	2.6	1.8
Weightman and Amis (1982)	40, 30, 40, 10	2.9	5.4	6.1	2.6	2.1	2.0
Smith *et al.* (1964)	40, 30, 40, 10	—	—	7.5	2.1	3.8	2.5
Present model	60, 20, 20, 10	3.2	6.0	6.4	1.8	2.9	2.4
Weightman and Amis (1982)	60, 20, 20, 10	3.2	5.9	6.4	1.8	2.7	2.4
Chao and An (1978b)	60, 20, 20, 10	4.7	8.3	8.6	2.4	3.3	3.1

because the PIP joint flexion angle increases and the MP flexion angle decreases slightly. Both of these changes decrease the INT tendon moment arms about the PIP and MP joints. These effects influence the joint forces more than the slight decrease in fingertip force moment achieved by decreasing the key contact angle from 80 to 45°. Moving from position 2 to 3, all joint forces (except the PIP joint force) and stresses increase again, because the PIP joint flexion angle is again increased. Note that the INT tension is maximum at this position. The forces would be even higher if the MP joint flexion angle had not increased slightly from position 2 to 3.

All tendon and joint forces and stresses decrease in position 4 of Fig. 5 based solely on the increase in MP joint flexion angle (from position 3). They generally decrease even further in position 5, due to the decreased key contact angle that minimizes the moment of the fingertip force about each of the joints and the slightly greater MP joint flexion angle that increases the mechanical advantage (i.e. moment arm) of all tendons passing volar to the MP joint center.

The articulating joint stress data in Fig. 5 correlate well with clinical observations (Moran, 1977), that show osteoarthritis to be more common in the DIP and PIP joints than in the MP joint, and to be more common in females, who have 72% smaller average contact areas than males. The joint stress magnitudes shown in Fig. 5 are average stresses over the contact area; actual peak stress would be higher.

The nearly vertical optimal finger position suggested by the MP joint force and FDP tendon tension minimizations (Figs 6 and 7) is not commonly utilized by pianists, but provides valuable information if analyzed more closely. The large MP flexion angle increases the moment arms (and the mechanical advantage) of the FDP and FDS tendons, greatly reducing their tensions and the joint reaction force for a given load. The moment of the fingertip load about the MP joint is minimized in this position, further reducing each of the joint reaction forces when the three remaining angles are small. The combined effects of increasing tendon moment arms at the MP joint and increasing fingertip load moment are shown in Fig. 8. As the MP flexion angle, and thus tendon moment arms about that joint increase, joint reaction force decreases. Also, as PIP flexion angle, and thus fingertip moment about the MP joint [due to fixed key contact angle and $(\theta_1, +\theta_2+\theta_3)<90°$] increases, flexor tendon tensions must increase to balance the increased moment, increasing joint force.

Detrimental finger positions, such as the maximum joint force positions (Fig. 6) determined by minimizing the inverse joint force, may be of greater interest to pianists. Positions with PIP joints flexed and DIP and MP joints extended (positions 12 and 14) maximize DIP and MP joint reaction forces. Generally, an extended joint in combination with a large key contact angle (position 13) produces maximal PIP joint force. It is interesting to note that the famous pianist Horowitz successfully used finger key strike positions similar to position 13, but traveled with his own customized piano with lighter keys that reduced the overall finger forces.

Since the FDP tendon not only flexes all finger joints but also extends the PIP and DIP joints through the lumbrical (LU) tendon, its functions are somewhat counterproductive providing joint stability through over-constraint. The lumbrical passes dorsal to the PIP joint center alongside the proximal phalanx and its moment arm about the PIP joint decreases as the joint flexes. The result of this decreased moment arm is that the objective function is maximized at a moderate PIP joint flexion angle and reduced at higher and lower PIP joint flexion angles. This reduction is due to the fact that the more volar FDP branch of the tendon increases its moment arm about the joint when PIP flexion is maximized, and the more dorsal LU branch (through the ES tendon) of the tendon has a larger moment arm when the joint is extended. This is also true for the INT tendon tensions, which all pass volar to the MP joint, assisting in MP flexion, but dorsal to the PIP and DIP joints, thus, over-constraining these joints. Increased MP flexion is beneficial in that the moment arms (about the MP joint) of the UI, RI and LU tendons increase (as does their mechanical advantage and fingertip force-balancing ability) as the MP joint flexes.

In conclusion, finger key strike positions that minimize the fingertip force moments at the joints, especially the MP joint, and maximize flexor tendon moments about the joints will generally minimize all finger forces. This force reduction is achieved by using a generally curved finger key strike position with a relatively large MP flexion angle. Finger positions with a moderate PIP flexion angle but low MP flexion angle maximize INT muscle tensions. Since the intrinsic finger muscles are smaller and weaker than the extrinsic muscles, these positions should be avoided when possible. Finger positions with moderate key contact and PIP flexion angles (but low DIP and MP flexion angles) maximize MP and DIP forces and FDP tendon tension, yet minimize FDS tendon tension. The position required for minimum MP and PIP force which consists of low key contact, low DIP and PIP flexion angles and high MP flexion angle requires a highly flexed wrist position, which is undesirable in sustained piano playing because of median nerve compression. A generally curved finger position promotes neutral wrist position and thus minimizes potential nerve compression syndromes.

Although studies correlating injury occurrence rates with finger joint positions and key strike styles are yet to be performed, it seems obvious that using force-reducing positions should reduce injuries. Use of the more curved position number 5, in Fig. 5, should result in a lower incidence of performance-related injury compared with the other four commonly used finger positions.

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