

# Loudness control in pianists as exemplified in keystroke force measurements on different touches

Hiroshi Kinoshita<sup>a)</sup> and Shinichi Furuya

Graduate School of Medicine, Osaka University, 2-2 Yamadaoka, Suita, Osaka 565-0871, Japan

Tomoko Aoki

Faculty of Environmental and Symbiotic Sciences, Prefectural University of Kumamoto, 3-1-100 Kumamoto City, Kumamoto 862-8502, Japan

Eckart Altenmüller

Institute of Music Physiology and Musicians' Medicine, University of Music and Drama Hanover, Hohenzollernstrasse 47 D-30161 Hannover, Germany

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The relationship between the key depression force on an upright piano and the level of loudness of a generated tone was examined when pianists hit a force-sensor built-in key with “struck” or “pressed” type of touch. The vertical displacement of the key, and the radiated piano sounds were also recorded. It was found that for both types of touch, simple exponential functions could adequately describe the relation of the force amplitude with the level of the piano tone as well as that of the impulse of the force with the piano tone. The impulse of the force generated before the maximum key depression moment commonly amounted to above 80% of the total impulse produced at the tone below *mezzo-forte*. It, however, decreased to around 60% at *fortissimo*, indicating a decrease in the efficiency of the force application for sound production. The two types of touch differed in their force profiles. The struck touch was characterized by a steeper initial force increase with greater fluctuations in the subsequent period than the pressed touch. The struck touch also demonstrated lower maximum force and less impulse at *fortissimo*. The inter-pianist variation in the force and impulse, and the “finger-noise” are also herein examined. © 2007 Acoustical Society of America. [DOI: 10.1121/1.2717493]

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## I. INTRODUCTION

Playing the piano undoubtedly represents one of the most complex sensori-motor skills that humans may acquire, requiring years of training. Striking the key to generate the required level of loudness is a fundamental and indispensable component of a pianist's skill. The keystroke commonly starts with a downswing of the arm toward the key, and ends with the application of regulated depression force by the fingertip on the front side of the key. The key itself moves in a “see-saw”-type of motion via a balance-rail bearing as the player presses the key. The applied downward force thus acts on a complex hammer-driving structure resting on the other side of the key via an assembly called a “whippen jack.” Shortly before the hammer contacts the string, the transmission of force from the key to the hammer is interrupted and the hammer is left swinging freely against the string, allowing an effective transfer of kinetic energy from the hammer to the string for sound production (Fletcher and Rossing, 1998).

An understanding of the force or impulse acting on the key by the finger is important because it is the sole source of kinetic energy to move the hammer. Hence, it can be a major variable for pianists to modulate the volume or pressure of

the generated sound. When considering the nature of sound in addition, the manner in which pianists apply force to the key must also be included as a variable. Two different fundamental techniques of key touch may be of interest in this respect. One technique is the so-called “struck touch,” where the key is struck by a moving finger, and another is the “pressed touch,” when the key is pressed by a finger resting on its surface (Goebel *et al.*, 2005). The force generated between the finger and the key (“finger force”) can also be regarded as a source of stress on the pianist's hand as it may reach a relatively large magnitude immediately after the moment of key-front rail contact (Harding *et al.*, 1989). Repetitive application of such stress is considered to be one of the major causes of musculoskeletal problems in keyboard players (Amadio and Russotti, 1990; Caldron *et al.*, 1986; Fry, 1991).

Some efforts have been made to study the force applied by the finger on the key (finger force) in the past. Using a thin force sensor foil inserted into the space between the key and front rail in the key bed, Parlitz *et al.* (1998) measured the depressing force of the finger against the front rail while performing so-called “tied-finger exercises,” i.e., some fingers were depressing piano keys and holding them down for the entire exercise, while the remaining fingers executed the key stroke. Groups of expert and amateur players performed three tied-finger exercises with increasing degrees of difficulty while the loudness level was kept constant at around a

<sup>a)</sup>Author to whom correspondence should be addressed. Electronic mail: hkinoshita@moted.hss.osaka-u.ac.jp

*forte* (*f*) level. They found that the amateurs used greater tied-finger forces as well as keystroke forces, and a longer force application period by the striking fingers compared with the experts on playing the same notes. They concluded that years of piano training allow for pianists with an independent coordination of playing and nonplaying fingers after touch and a sense for the piano's response.

Using a force transducer mounted on the key surface, Harding *et al.* (1989) directly measured finger force at a moderate loudness level during *staccato* and *legato* strikes by subjects with different skill levels. The finger force after the moment when the key reaches its maximum displacement ("bottom out") cannot contribute to sound production. Therefore, they computed the value of impulse (the area under the force-time curve) generated prior to the bottom-out moment. Since they did not measure key displacement, they assumed that the bottom-out moment corresponded to the onset moment of the highest peak force. The findings indicated that this impulse value did not differ between the *staccato* and *legato* strikes when producing the same level of loudness. The impulse values had a nonlinear relationship with key velocity. The force profiles shown in their study also suggested that the impulse generated from the key touch to the bottom-out moment was smaller than the impulse generated after the bottom-out moment.

Using a similar force measurement system, Askenfelt and Jansson (1992) measured the finger force at various loudness levels. The number of pianists as well as the force sensor type used was not mentioned in their article, and the description of the force characteristics was limited. Nevertheless, they provided important information about the magnitude of maximum finger force in relation to sound loudness. They stated that at *piano* (*p*), *mezzo forte* (*mf*), and *fortissimo* (*ff*) levels with *staccato* touch, the peak force reached around 8, 15, and 50 N, respectively. In *legato* touch, the finger forces were considerably lower during acceleration, typically one third or even less at the softest levels.

It is apparent from these reports that little work has been done to investigate the nature of force imparted by the finger on the piano key. Especially, detailed finger-force information based on a larger number of pianists is lacking. It is also necessary to have a key in which a force sensor is built in and the sensor surface is flush with the key surface so that any psychological factor influencing the control of keystroke movement is minimized. In the present study, therefore, using a force transducer built-in key, we made a more complete analysis of the relationship between the finger force and level of sound pressure (SPL) using ten expert pianists who performed keystrokes with struck and pressed touches.

## II. METHODS

### A. Subjects

Eight female and two male active classical pianists (age =  $21.6 \pm 1.7$  yrs., height =  $163.6 \pm 8.8$  cm, weight =  $52.1 \pm 10.1$  kg) who showed no serious playing-related physical problems in the past served as the subjects in the present study. Each pianist had at least 15 years of training

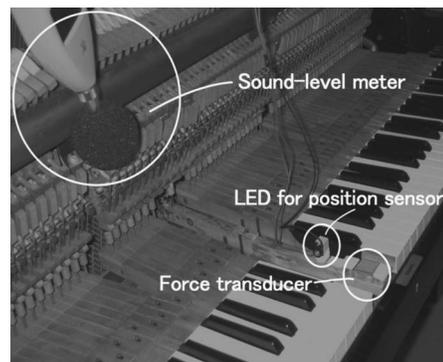


FIG. 1. Experimental setup.

with experience of winning a prize(s) at high-level domestic (Japan) and/or international piano competitions. Informed consent was obtained from each subject prior to the experiment, and the study was approved by the Ethics Committee for Human Research at Osaka University.

### B. Finger force, key displacement and sound data acquisition methods

The finger force was measured using a strain-gauge-type miniature uniaxial force transducer fixed to the distal end of a C4 key of a Yamaha upright U1-model piano (see the "force transducer" in Fig. 1). The transducer was designed and built for the purpose of this study based on our previous work (Kinoshita *et al.*, 1995). Therefore, the measurement range of 0–100 N within a 0.5% error in linearity was chosen. The resolution of the transducer was 0.02 N. The natural frequency of the unloaded force transducer was DC–1 kHz. The force signal was amplified using a Kyowa strain gauge amplifier and stored on a SONY personal computer via a 12 bit analog-to-digital (A/D) converter sampling at a frequency of 900 Hz. The vertical movement of the key was also recorded using a Hamamatsu photosonic light-spot two-dimensional position measurement system interfaced with a personal computer. The light-spot LED was placed 1.5 cm above the key surface and 8 cm from the front edge of the key (see the "LED for position sensor" in Fig. 1). The key displacement data recorded were smoothed at a cut-off frequency of 24 Hz using a second-order Butterworth digital filter. Vertical velocity and acceleration were then calculated using a numerical differentiation method. Three adjacent keys (B4, C4, and D4) were removed from the piano to assure the free space for the transducer wires.

During the experiment, radiated piano sounds were synchronically sampled using a RION sound-level meter placed 20 cm above the key (see the "sound-level meter" in Fig. 1), which was then amplified using an audio amplifier to feed into the personal computer via an A/D converter sampling frequency at 900 Hz.

The experimental room was an ordinary temperature-controllable room. The background noise level was around 50 dB. This relatively louder background noise level was due to numerous machines in the experimental room.

### C. Key-striking task

The key-striking task was a series of slow- and self-paced (freq. = approx. 0.3 Hz) repetitive keystrokes with very short duration. The length of each tone generated was instructed to be a 16th note without holding each tone, and thus in a *presto* tempo. For each subject, data were collected from a series of 60 strokes at varied SPLs for each of the two prototypical types of touch: depressing the keys with the finger initially resting on the key surface (pressed) and hitting the key from a certain distance above (struck) (Askenfelt and Jansson, 1991; Goebel *et al.*, 2004; 2005). To obtain SPLs distributed approximately evenly over the whole range between the maximum and minimum, the following instruction was given to each subject prior to the series for each touch: "During the initial 15 strokes, please increase the level of sound generated gradually and voluntarily from the minimum to the maximum level, and during the following 15 strokes, please decrease the generated sound gradually to the minimum level. Please repeat the same process during the following 30 strokes. Please count the number of strokes silently for each of the 15 strokes." At the end of the experiment with each subject, the collected and stored data were checked to have a total of 120 keystrokes (60 struck and 60 pressed).

As an initial hand position common to the struck and pressed touches, each subject was instructed to place his/her right middle finger by lightly ( $>0.03$  N) touching its tip on the C4 key while the tips of the thumb and little finger were also lightly touching the A4 and E4 keys, respectively. The index and ring fingers were kept in the air because the B4 and D4 keys were not present. The left arm and hand were relaxed and kept on the left thigh during the experiment.

For the struck touch, from the initial hand position, the right arm was lifted to a self-determined distance above the key surface at self-determined natural speed. From this lifted position, the arm was dropped and the C4 key was struck by the right middle finger to generate piano sound. After this, the whole arm was immediately lifted again as a follow through to a self-determined height. The hand was then returned to the starting position at the self-determined speed to prepare for the next keystroke.

For the pressed touch, there was no arm lift prior to a keystroke. The C4 key was therefore pressed by the right middle finger to generate sound from the initial hand position without any preparatory arm lift. After the keystroke, however, the whole arm was immediately lifted as a follow through to a self-determined height similar to the case of the struck touch. After this, the hand was lowered to the starting position to prepare for the next keystroke.

Prior to the experiment, each subject practiced these experimental tasks until they felt comfortable performing them.

### D. Parameters evaluated

For the computation of sound pressure, the peak amplitude of the absolute value of the sampled sound data as a voltage was used (Palmer and Brown, 1991). The voltage value ( $V$ ) was then converted to a SPL representation in dB using the following equation:  $SPL = L_0 + 10 \log_{10}$

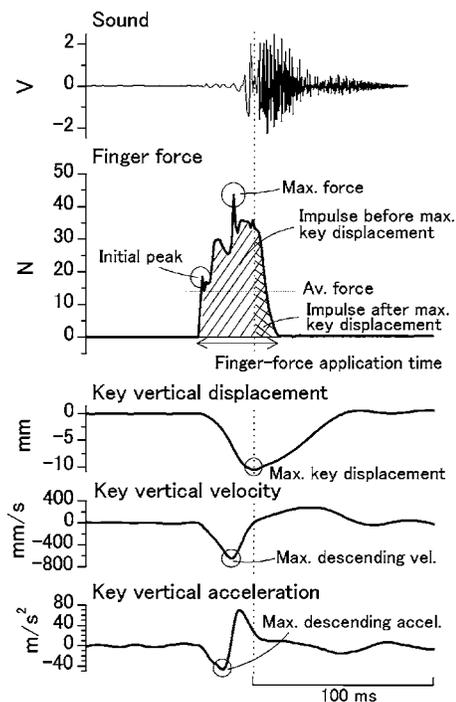


FIG. 2. Representative sound, finger-force, key-displacement, key-velocity, and key-acceleration curves during striking the key with a struck touch. Some of the parameters evaluated are also shown.

( $V^2/(V_0/\sqrt{2})^2$ ), where  $L_0$  and  $V_0$  indicate the dB value and the corresponding voltage value of fundamental sound, respectively.

Nine variables describing the finger force and kinematics of the key were computed from each trial data set for each subject, and used for the evaluation in the present study (Fig. 2). These were: (1) the finger-force application time as defined by the duration between the onset ( $<0.06$  N) and termination ( $>0.06$  N) of finger-force application for the keystroke, (2) initial peak force, (3) maximum force, (4) average force during the finger-force application time, (5) total impulse as defined by an integration of the force during the finger-force application time, (6) impulse over the period between the onset of finger force for the keystroke and maximum displacement of the key, (7) impulse over the period from the maximum key displacement to the termination of the finger force, (8) maximum displacement of the key, and (9) maximum descending acceleration of the key. The maximum key descending velocity was also computed, but it was not used for evaluation in the present study.

## III. RESULTS

### A. Finger force profiles

Figure 3 shows typical examples of time history curves for the sound signal, finger force, and key displacement from one subject with the struck (the upper panel) and pressed (the lower panel) types of key touch at three different SPLs (95, 103, and 111 dBs). These SPLs corresponded to typical *pp*, *mf*, and *ff* levels with the present piano according to the subjective judgment of the present subjects.

The force profiles for the struck touch (see also Fig. 2) were characterized by a rapid rise in force immediately after

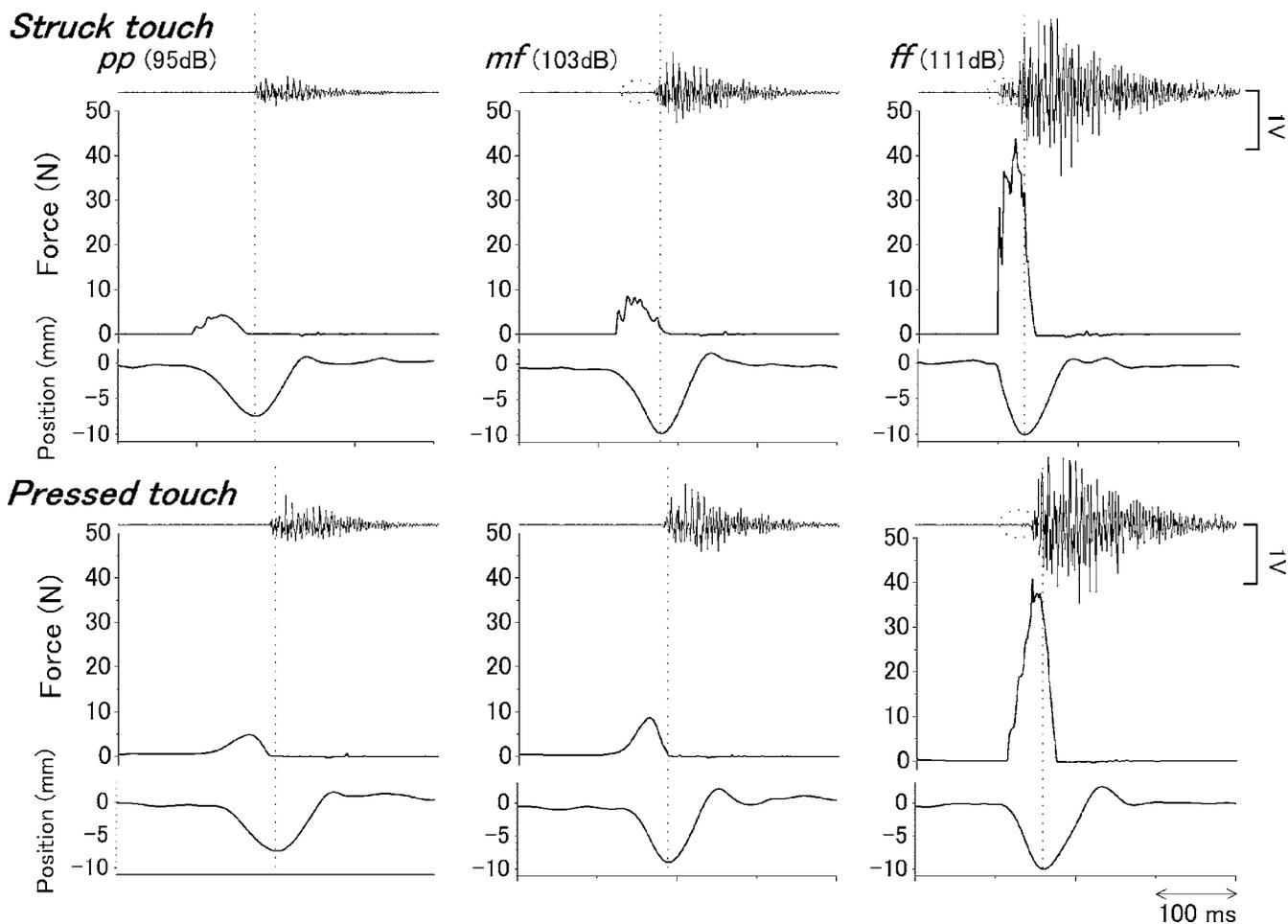


FIG. 3. Representative profiles of finger force, key displacement, and sound from selected trials (*pp*, *mf*, and *ff*) of one subject with struck (upper panel) and pressed (lower panel) types of key touch. The dotted line indicates the moment of maximum key displacement. The touch noise is indicated by a dashed circle in the sound signal.

the finger contacted the key, which produced an initial peak at 3–5 ms after contact. The force then rapidly dropped to show a distinct trough after another 3–5 ms from the peak. The force was then developed again, and formed multiple peaks until the end of the finger-force application time. The sound signals indicated that at all SPLs, the piano sound was generated after the appearance of the maximum finger force. The key displacement curves demonstrated that the key started to move soon after the finger force was developed, and it reached the lowest position toward the end of the finger-force application time.

The force during a pressed touch developed more slowly than that during a struck touch (lower panel in Fig. 3). The initial peak of the force was less clear with the pressed touch, though a small step-like initial force increase was noted in some cases, especially when generating louder sound (see the force curve at *ff*). The subsequent force with the pressed touch was also less variable than that with the struck touch. Similar to the struck touch, the piano sound was generated after the appearance of the maximum finger force, and also the moment of the maximum key displacement occurred near the end of the finger-force application time.

### B. Maximum force, total impulse, and finger-force application time in relation to SPL

Figure 4 shows typical examples of the maximum force, average force, total impulse, and finger-force application time as a function of SPL generated by one subject during the struck (upper panel) and pressed (lower panel) types of key touch. For both touch types, the forces and impulses increased curvilinearly with an increased SPL, while the finger-force application time decreased linearly with SPL. An attempt was made to fit simple mathematical functions to describe the curvilinear relationship of the force and impulse parameters of each subject. It was found that an exponential function ( $F = A \exp(B \cdot \text{SPL}) + C$ , where  $F$  = finger force,  $A$ ,  $B$ , and  $C$  are constants) was sufficient to describe the relationship rather precisely compared with six other functions tested. With this curve fitting, the proportions of variance ( $r^2$ ) computed for the maximum force for each subject ranged from 0.81 to 0.98 (mean  $\pm$  SD =  $0.91 \pm 0.05$ ), and those for the total impulse were from 0.83 to 0.96 (mean  $\pm$  SD =  $0.88 \pm 0.04$ ). The corresponding values for the pressed touch were from 0.87 to 0.96 (mean  $\pm$  SD =  $0.93 \pm 0.03$ ) for the maximum force, and from 0.75 to 0.96 (mean  $\pm$  SD =  $0.86 \pm 0.09$ ) for the total impulse. The finger-force applica-

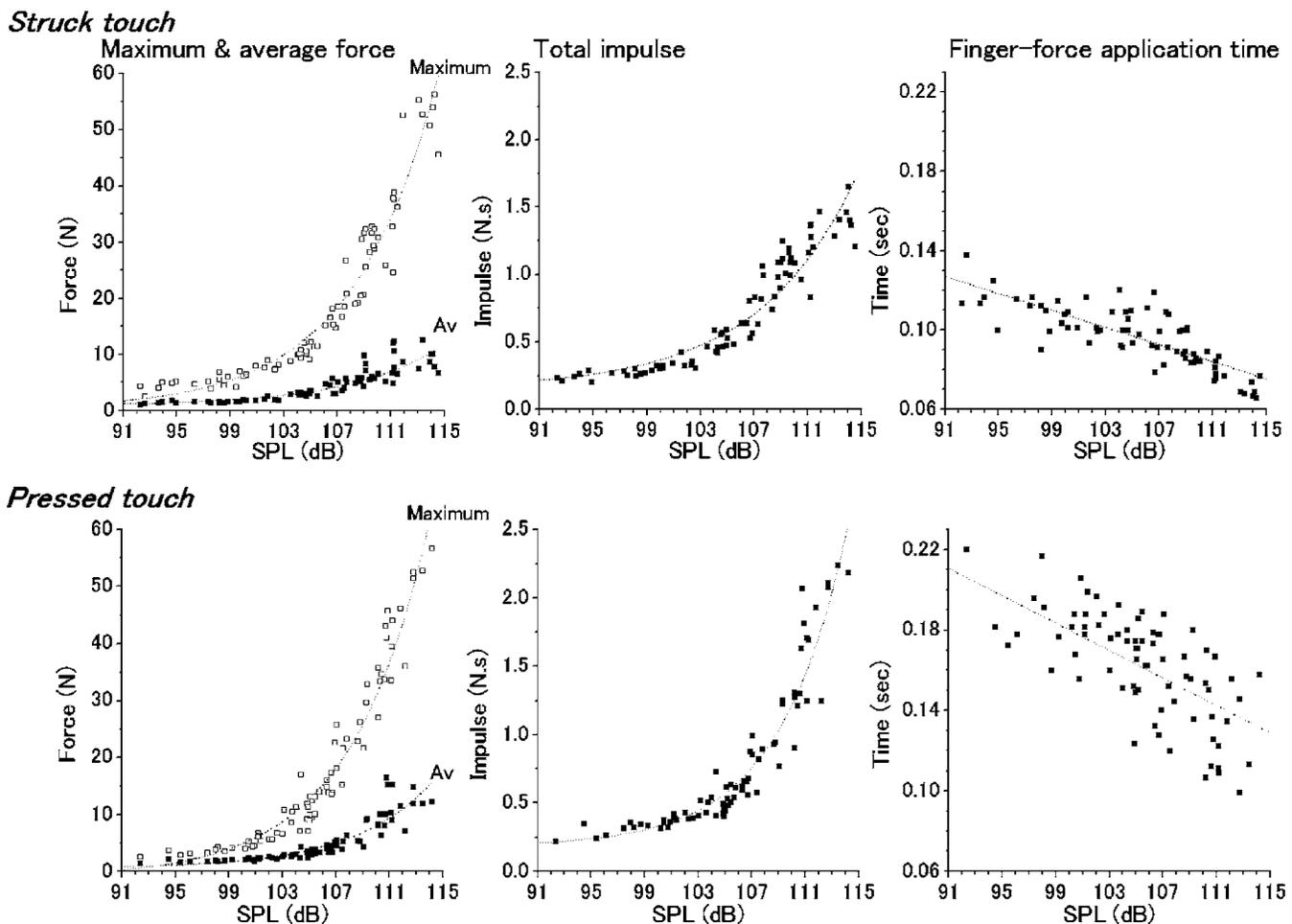


FIG. 4. Changes in the maximum force, average force, total impulse, and finger-force application time with SPL of one subject with the struck touch (upper panel), and the pressed touch (lower panel). The line in the figure indicates a fit curve for the data. The data are from the same subject in Fig. 3.

tion time decreased linearly with SPL in all subjects for the struck touch (mean  $r^2 \pm SD = 0.79 \pm 0.12$ ) and the pressed touch (mean  $r^2 \pm SD = 0.68 \pm 0.09$ ).

A simple exponential function also fitted relatively well with the maximum force and total impulse data pooled across all subjects (Fig. 5). The  $r^2$  values computed for the maximum force were 0.78 for the struck touch and 0.81 for the pressed touch. The  $r^2$  values computed for the total impulse data were 0.66 for both types of key touch.

### C. Impulse before and after maximum key displacement

Since the piano sound is generated by finger force to move the key downward, the impulse of the force produced during the period of downward movement should reflect the physical effort of the pianists for the production of an intended SPL. Any force applied to the key after the attainment of maximum key displacement may then be wasted in terms of sound production. Impulses generated both before and after maximum key displacement were computed for each keystroke for all subjects. In Figs. 6(A) and 6(B), the before- and after-values of the impulse are plotted in relation to SPL for both types of key touch. With an increase of SPL, the before- and after-values were increased in a curvilinear fashion.

The efficiency of finger force action was assessed by computing a proportion of the before value of the impulse to the total impulse produced. The computed value decreased from nearly 100% at lower SPLs to around 65% at higher SPLs with means and SDs of  $82.5 \pm 9.0\%$  for the struck touch and  $80.4 \pm 12.2\%$  for the pressed touch (Figs. 6(C) and 6(D)).

### D. Comparison between the struck and pressed touch modes

Finger force was compared between the two types of key touch at different SPLs. For this purpose, the SPL data between 93 and 113 dBs were arbitrarily sorted into five categories roughly corresponding to musical dynamics indication with each being 3.99 dB wide. Within each of these dB categories, the mean values for the maximum force, impulse before the maximum key displacement, and maximum acceleration were computed for each subject, and subsequently for all subjects (Fig. 7). At each SPL category, a “planned comparison” using one-way analysis of covariance (ANOVA) with repeated measures was performed for each of these force and acceleration variables as a dependent variable and the touch mode as an independent variable (see, the explanation about the “planned comparison” in Keppel, 1991). There was a significantly higher maximum force ( $F_{1,9}$

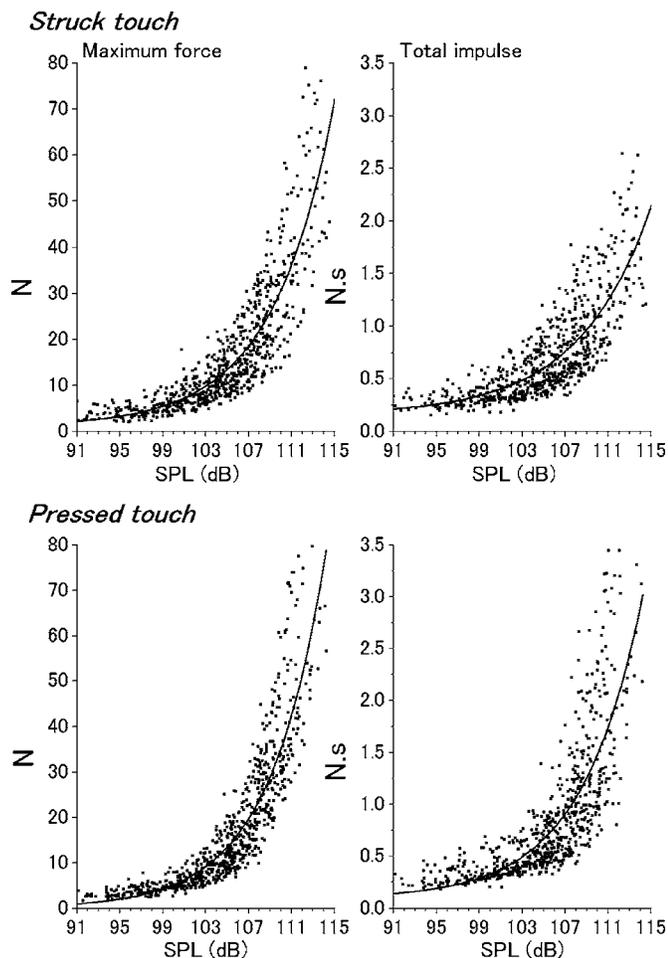


FIG. 5. Changes in the maximum force and total impulse with SPL of all subjects for the struck (upper panel) and pressed (lower panel) types of key touch. The line fit was made using a simple exponential function.

$=6.79$ ,  $p < 0.05$ ) and impulse ( $F_{1,9}=7.07$ ,  $p < 0.05$ ), and a smaller descending acceleration ( $F_{1,9}=18.3$ ,  $p < 0.001$ ) for the pressed touch than for the struck touch at the highest SPL range (109–113 dB) (Fig. 7). At the lower SPL range (97–100.99 dB), on the other hand, the struck touch had a higher maximum force ( $F_{1,9}=10.78$ ,  $P < 0.01$ ).

### E. Inter-subject variation in finger force

In Fig. 8(A), maximum forces are plotted separately for all ten pianists playing with the pressed touch only. Fit curves of the force- or impulse-SPL relationship exhibited a clear variation in the absolute value of applied force among the pianists especially when producing louder sound. To assess inter-subject variation at each of the dynamic categories as defined above, the coefficient of variation values (CV in %) for the maximum force and impulse were computed by dividing the SD by the corresponding mean. The CVs ranged between 27 and 31% across all ranges of SPL without showing any increasing or decreasing trend with SPL.

Why are the finger forces of individual subjects different when simply striking the same key and producing the same level of sound? One explanation for this may be because of the difference in pianists' body mass; heavy pianists with a larger upper body mass strike the key with greater force. We

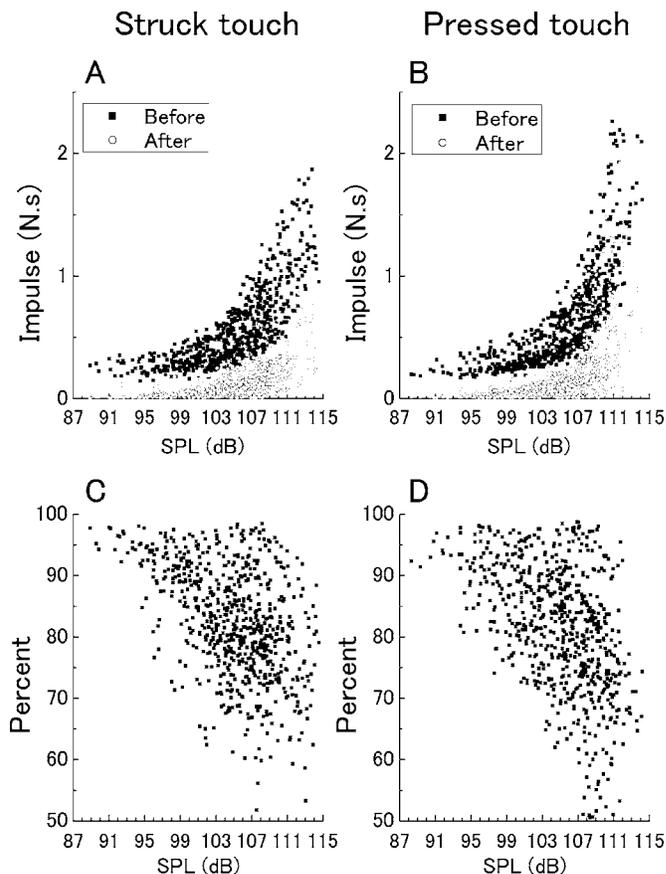


FIG. 6. Impulse before and after maximum key displacement in relation to SPL for all subjects with struck (A) and pressed (B) types of key touch, and percent values of impulse before the maximum key displacement relative to the total impulse for the struck (C) and pressed (D) types of key touch.

therefore examined the relation between the maximum finger force and body weight of the subjects for each of the above-defined five SPL ranges. In Fig. 8(B), the relations for the 93–96.99, 101–104.99, and 109–113 dB ranges are shown as examples. Note that the correlation values computed were quite small, and they were all statistically insignificant (see Fig. 8(B)). The  $r$  values for the 97–100.99 and 105–108.99 dB ranges were  $-0.067$  and  $-0.209$ , respectively. Plots for these data are not shown in Fig. 8(B) because they could overcrowd the figure.

Although the entire mass of the body is not a related factor of the maximum finger force, another concept of mass, which is the “effective mass,” is yet to be examined since it reflects a more directly related portion of the body concerning the keystroke. The effective mass can be defined here as “a portion of the pianist body (mostly the upper extremity) that is accelerated to generate the external force,” and thus it is estimated by the measured force divided by its measured acceleration. A relationship between the maximum finger force and the ratio between the maximum force and maximum key acceleration as an estimate of the effective mass was thus examined (Fig. 8(C)). Significantly high correlations were found at all of the SPL ranges (see the  $r$  values of the 93–96.99, 101–104.99, and 109–113 dB ranges in Fig. 8(C)). The  $r$  values for the 97–100.99 and 105–108.99 dB ranges were  $0.696$  ( $p < 0.05$ ) and  $0.920$  ( $p < 0.005$ ), respec-

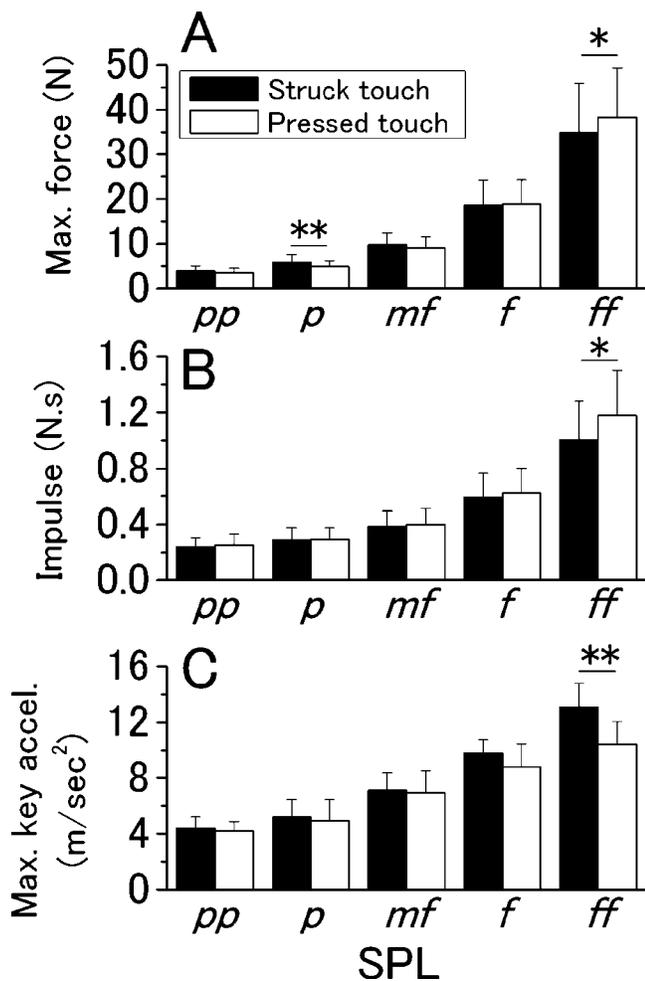


FIG. 7. A comparison between keystrokes with struck and pressed types of key touch for the maximum force (A), impulse before maximum key displacement (B), and acceleration of the key during the descending phase (C) for different dynamic categories (*pp*:93–96.99 dB, *p*:97–100.99 dB, *mf*:101–104.99 dB, *f*:105–108.99 dB, *ff*:109–113 dB). A planned comparison using one-way repeated measures ANOVA was performed at each of the SPL ranges. \* $p < 0.05$ . \*\* $p < 0.01$ . Error bars represent +1SDs.

tively. Therefore, from 49 to 87% of the variance for the maximum finger force may be explained by the effective mass. We also examined the relationship between the maximum force and maximum key acceleration, which was insignificant at each of the SPL ranges (Fig. 8(D),  $r = -0.100$  at 97–100.99 dB and  $-0.128$  at 105–108.99 dB).

### F. Finger-touching noise

The sound signals indicated that at all SPLs the piano sound was generated after the appearance of the maximum finger force. On the other hand, there was commonly a small but detectable sound signal starting immediately after the finger-key contact moment for the struck touch (see dotted circles in the sound signals of *mf* and *ff* of the struck touch in Fig. 3; also Fig. 2), and after a short period of force application for the pressed touch (see “*ff*” of the pressed touch in Fig. 3). This first soft sound has been termed “finger noise” or “touch precursor” (Goebel *et al.*, 2005), and is caused mostly by the finger or nail when it pounds or rubs the key surface. Using criteria of  $>59.0$  dB for the SPL and  $>5$  mm for the key position, we automatically detected and differentiated this noise from the background noise as well as the piano sound. For the struck touch, the onset of this signal coincided temporally with the occurrence of the initial finger-force peak.

A clear touch-related noise was detected in 560 keystrokes (93%) among the 600 keystrokes performed by ten subjects for the struck touch. The noise occurred  $40.1 \pm 18.2$  ms (mean  $\pm$  SD of the 560 observations) before the emergence of the piano sound. The noise SPL increased markedly from 62 to 65 dB at the initial peak force of 2–3 N to 90–100 dB at the peak force of 30–45 N (Fig. 9(A)). The piano SPLs corresponding to these finger noises were 90–95 dB and 110–115 dB, respectively. The difference between the SPLs of the finger noise and piano sound were therefore about 30 dB at *pp*–*p* levels and about 15 dB at *f*–*ff*.

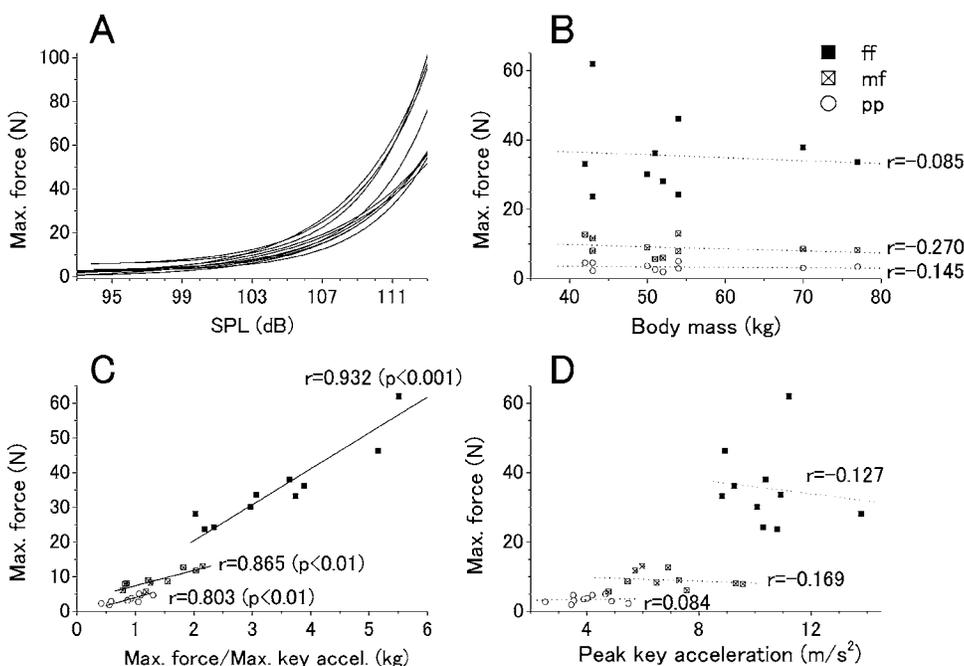


FIG. 8. Inter-subject variation in the maximum force-SPL relationship curves for all subjects with the pressed touch (A), and relationships between the maximum force and body mass (B), between the maximum force and an estimate of the effective mass (maximum force/maximum acceleration) (C), and between the maximum force and peak acceleration of the key (D). The maximum force and maximum acceleration in B, C, and D are the average values for each subject computed at *pp*, *mf*, and *ff* of the SPL ranges defined in Fig. 7. The data were computed only for the pressed touch. Lines indicate the regression lines computed.

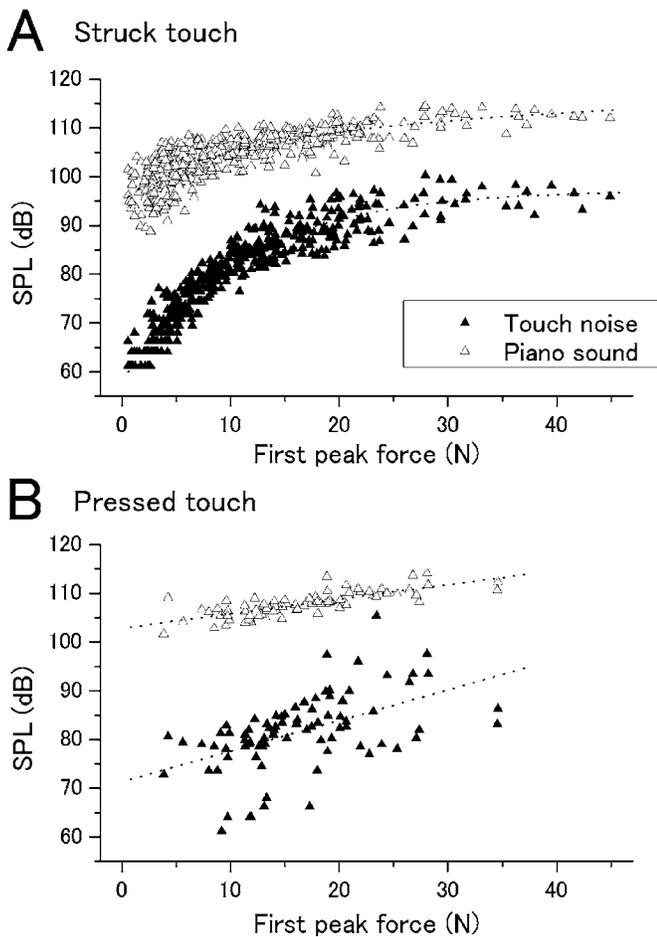


FIG. 9. Finger noise and related piano sound as a function of the first peak of finger force with the struck (A) and pressed (B) types of key touch. The data plotted are from all subjects. The dotted lines indicate best fit curves with a logistic function for the struck touch and a linear function for the pressed touch.

For the pressed touch, the finger noise-like signal was detected in 163 keystrokes (44% of 600 keystrokes for all subjects) from the automatic analysis of the data. Since the finger is not pounding the key during the pressed touch, we consider that it may not be safe to categorize these sound signals in the same way as the noise detected with the struck touch; it may be totally key-action-related mechanical noise. Of 163 keystrokes, 110 occasions had a detectable initial first peak of finger force, and therefore we tentatively plotted those in relation to the initial peak force (Fig. 9(B)). The noises ranged from 61 to 106 dB, which occurred  $23.9 \pm 7.3$  ms (mean  $\pm$  SD) before the emergence of the piano sound. The SPL difference between the piano sound and finger noise was about 25 dB for the pressed touch.

## IV. DISCUSSION

### A. Finger force at differing SPLs

The maximum finger forces observed in the expert pianists commonly ranged between 3 N at *pp* and 60 N at *ff*. Four of them also exceeded 60 N at *ff* or above. This force range was wider than those (8 N at *p* to 50 N at *ff*) reported by Askenfelt and Jansson (1992) due possibly to our slightly wider SPL range examined. However, it may also be attrib-

uted to differences in the ease of hitting the force sensor which is hidden under the key surface as in the present study, in contrast to a positioning on the top of the key in the latter study. A higher required level of accuracy in hitting the sensor (especially at *ff* in the latter setting) therefore could have caused a reduction in the attacking velocity.

Our results indicate that a simple exponential function can describe adequately the changes in the parameters of finger force in relation to SPL regardless of the key touch type. The increase of the maximum finger force with an increase in SPL, and therefore the force/SPL ratio, was quite small at low SPLs. However, it became very large at high SPLs. For example, at *pp* (from 93 to 96.99 dB), the ratio was around 0.4 N/dB, whereas at *ff* (from 109 to 113 dB), it became 6.5 N/dB for the struck touch and 8 N/dB for the pressed touch, showing a 16- to 20-fold increase. The adjustment of low sound intensities clearly demanded an extremely high level of force control. Conversely, at the highest SPLs, this demands the modulation of a large force output against the key. How are pianists coping with these contrasting demands? Our previous studies of the upper extremity movements of expert pianists who performed keystrokes at various SPLs demonstrated that the production of small SPLs was accomplished principally by exclusive movements of the fingers while keeping the proximal limbs relatively stable (Furuya *et al.*, 2006). The production of higher SPLs was, on the other hand, reached by increasing both the range and speed of joint movements in the proximal limbs. In addition, there was an increased activation level of the flexor-extensor muscle pairs of the whole upper limb at the moment of key contact. These findings suggested that SPL control was made principally by modulating the mass of the body portions involved in key depression, joint stiffness, and the attacking velocity and acceleration of the whole limb. Thus, the observed small finger force when generating and adjusting a *pp* tone could be a consequence of a small mass with a low stiffness depressing the key at a low velocity and acceleration, while the large force at *ff* was due to the combined effect of a large mass, high joint stiffness, and a high attacking velocity and acceleration. These findings are in agreement with suggestions from theoretical papers, e.g., Parncutt and Troup (2002).

The present study also demonstrated that a large portion of the finger force was generated before the key reached the bottom of its displacement. This is reasonable because the hammer-driving structure commonly starts to move when the key end descends beyond the halfway point (about 6 mm in the present experimental piano) of its movement range (10.5 mm). This movement range was about 1 mm larger than the grand piano reported in a previous study (Askenfelt and Jansson, 1991). Therefore, in theory, force application can be completely terminated before the key reaches the bottom of its movement range since any force applied to the key after the event of the hammer thrust cannot contribute to sound generation. The results of the present study indeed indicated that the impulse before the moment of maximum key displacement commonly exceeded 80% of the total impulse generated. This finding disagrees with that of Harding *et al.* (1989), who have shown that finger-force profiles in

*staccato* strikes have a larger peak and impulse during the period after the maximum key displacement (also the “bottoming-out” in their definition) moment than prior to it. This discrepancy appears to have resulted from the method used to determine the moment of maximum key displacement. Harding *et al.* used force data for this purpose under the assumption that the maximum finger force occurred at the moment of maximum key displacement when the key collided with the felt of the front rail. Our simultaneous recording of finger force and displacement indicates that this assumption is incorrect. As was shown in Fig. 3, the maximum force commonly appeared earlier than the moment of maximum key displacement. An extremely early case involves the trials at low SPLs, where the finger-key contact had been terminated before key displacement reached its maximum point (see “*pp*” in Fig. 3 as an example). In this case, the maximum displacement was only 6–7 mm, and therefore there was no collision of the key with the felt cushion on the front rail. At higher SPLs, on the other hand, the key vigorously hit the felt, and the time lag of the maximum force and maximum key displacement was shortened (see “*ff*” in Fig. 3). Nevertheless, the maximum key displacement was always detected after the event of maximum force, possibly due to depression of the felt which occurred after the event of key-felt collision.

The above findings also indicate that some portion of the post key-bottom force (<20% of the total impulse) is difficult to avoid, especially when producing a louder sound. There are several reasons for this. One is that when producing a louder sound, switching of the movement direction from downward to upward at an exact moment becomes more difficult due to momentum (larger segmental mass moving at a faster velocity). Under such conditions, the probability of a delayed switching of movement becomes higher. Related to the difficulty of minimizing the post-bottom finger force as well as the time of force application at a high SPL, Parlitz *et al.* (1998) provided evidence that its impulse was larger, and the time was longer for less skilled players than skilled professional players. Second, when producing a louder sound, key depression is commonly made using a coupled flexion movement at the wrist and shoulder joints (Furuya *et al.*, 2006). This maneuver facilitates a thrusting forward motion of the whole arm to accomplish a more vigorous key depression. However, it also demands a longer finger-key contact time for longer force application to the key.

In the present study, the on-off timing of the key contacting with the front rail was not monitored. This was because in many of the keystrokes at *pp* and *p* tones and even some at an *mf* tone, the key did not hit the felt (bottom) of the front rail with the present fast *staccato* touch. According to Askenfelt and Jansson (1990), however, the key bottom contact is an important mechanical event providing sensory feedback from the instrument, decisive for the player’s ability to perform the desired timing and synchronization of the notes. Therefore, in a future study, analysis of finger force should include this temporal information for the better understanding of finger-force control by pianists (Parlitz *et al.*, 1998).

## B. Inter-subject variation in finger force

A relatively large inter-pianist variation was noted in the maximum force and impulse during key attack, showing that the same target SPL could be attained by the application of different levels of finger force. This may be of interest from the view of stress reduction since the repeated application of excessive finger force has been considered a risk factor of over-use injuries in musicians including pianists (Amadio and Russotti, 1990; Caldron *et al.*, 1986; Fry, 1991; Zaza and Farewell, 1997). The present study also demonstrated that the inter-pianist differences in force were related to the mass involved in key depression (effective mass) but not to an individual’s body weight. The force was also unrelated to key acceleration. These findings suggest that the adjustment of effective mass, and thus the modulation of rigidity of the muscles in the hand and arm, is a key factor for the stress-related problems induced by finger force. This may have an important implication in the prevention of over-use injuries.

## C. Finger force of struck and pressed touches

The type of key touch clearly differentiated the pattern of finger-force development. For the struck touch, the initial force increase was rapid and formed a distinct key-touch-associated peak, followed by many peaks in the subsequent phase. For the pressed touch, on the other hand, the initial force increase was less steep without any initial peak, and it showed less force fluctuation in the mid-depression phase than the struck touch. Surprisingly, despite these clear differences in the force profile, we found that the maximum force and impulse exerted on the key were quite similar between the two touch types at the same SPL except when the subjects exerted a large force at *ff*. These findings, therefore, suggest that, at least with *staccato* articulation, SPL is largely determined by how forcefully the pianists press or strike the key, and not by how smoothly they apply force.

Goebel *et al.* (2005), who recently compared these two types of keys touch, reported that with the pressed touch, both of the key and hammer velocities developed much smoother and their spatio-temporal features had better correspondence than those with the struck touch especially when producing louder sound. Indeed, the velocity profiles shown in their study clearly described that for the struck touch, there was a period immediately after the finger-key contact where key velocity was increased markedly, but hammer velocity remained nearly unchanged. This observation led them to suggest that the pressed touch was more efficient than the struck touch. We, on the other hand, found that at the same SPL of *ff*, the pianists exerted a significantly larger finger force with the pressed touch than the struck touch. Therefore, contrary to the suggestion by Goebel *et al.*, our data reflecting the effort of force to move the key suggest that the pressed-touch method is less efficient (possibly demanding greater muscular effort) than the struck-touch method in loud sound production.

The computed descending acceleration of the key was significantly less with the pressed touch, possibly due to an inability to promote a rapid acceleration of the key from zero acceleration within its limited movement range. The results

indicated that compensation for this problem occurred by increasing the mass involved in pressing the key, which was indeed overcompensated. The reason for this overcompensation was uncertain, but we speculate that the adjustment of effective mass, which involved both the number of muscles and limb stiffness, may be more difficult than the adjustment of limb acceleration.

#### D. Finger noise

In agreement with the findings of previous studies (Askenfelt, 1994; Goebel *et al.*, 2004; Koornhof and van der Walt, 1994), in the present study, a short period of finger noise prior to a large piano sound was exclusively detected in the vast majority of strokes with the struck touch. In the pressed touch, there was also a finger noise-like single prior to the piano sound in some trials above *mf* levels. This smaller number of observations in the pressed touch is obviously due to the fact that the finger noise is caused mainly by the fingertip hitting the key. Detection of a similar noise without hitting the key in the pressed touch indicated that the noise could also be caused by the fingertip or the nail scraping the key surface when depressing the key at fast speed.

The present study also demonstrated that the amplitude of the initial peak force appearing within the first 5 ms contact period was related closely to the SPL of touch noise. The finding that a descending movement of the key did not commonly occur until the end of this short force pulse suggested that a large portion of kinetic energy resulting from this initial force application had been dissipated as noise rather than key movement. An additional observation related to touch noise was that, in all subjects, the SPL exceeded 90 dB at *ff*, which happened to be equivalent to the SPL of piano sound at *pp*. The noise must therefore be at an audible level even for listeners at a certain distance from the piano. Goebel *et al.* (2004), who studied the perception of touch noise in tone production, reported that only some trained musicians were able to distinguish between a struck and a pressed touch using this noise as a cue. When the listeners were unable to hear the touch differences, they tended to rate louder tones as being struck and soft tones as being pressed. The authors therefore speculated that the pure aural effect of touch noise on piano sound was relatively small. The finding in this study that the SPL difference between piano sound and finger noise was always greater than 15 dB supports their assumption; although the touch noise is audible, the subsequent piano sound is large enough as well as short enough (<50 ms) to mask its effect, due to the physiological mechanisms of backward masking (Yost, 2000).

#### E. Limitations of the study

Only one kind of small upright piano was used in the present study. In the previous studies of finger-force measurement, on the other hand, a grand piano has been commonly used (Askenfelt, 1994; Askenfelt and Jansson, 1991; Harding *et al.*, 1989; Parlitz *et al.*, 1998). There are apparent differences in the mechanics and acoustics between upright and grand pianos (Fletcher and Rossing, 1991, 1998). The grand piano has a more complex key action mechanism with

a greater number of moving parts (i.e., a larger mass and more mechanical frictions in general) to move the hammer vertically (i.e., a greater effect of gravity) compared with the upright piano having a less complex mechanism with a horizontal hammer motion. These mechanical differences may allow pianists with a better feel of the hammer weight, a more detailed and accurate regulation of key action, and thus a finer sound voicing for the grand piano. Pfeiffer (1978) earlier compared mechanical efficiency of grand and upright piano actions by dropping weights onto piano keys and determining the resulting kinetic energy imparted to the hammers (see summary tables (pp. 314–315) given in a book by Fletcher and Rossing, 1991). The upright piano has a slightly higher mechanical efficiency of this energy transfer than the grand piano at below an *mp* tone, which is reversed from an *mf* tone on. Therefore, in the upright pianos, there could have been less finger force required at very soft dynamics to produce a piano tone while greater finger force at louder dynamics compared with the grand piano.

Sound dampers are also more effective in grand than upright pianos, providing a difference in the quality of the tone produced. Acoustical advantages of the grand piano due to its larger size with longer strings and horizontal positioning of the soundboard also provide a greater range of SPL due to larger resonance and more sound reflection, and more radiated sound than the upright piano. All of these features potentially influence the finger force action on the keys, and thus the force-sound relationship. Some of the differences between our results and those of previous studies as discussed above, therefore, can be attributed to these upright and grand piano differences. A comparative study using other kinds of upright as well as grand pianos is therefore needed in the future.

Another limitation of this study was that we measured only the vertical component of finger force under the assumption that forces acting in the fore-aft and medial-lateral directions were small. The validity of this assumption may need to be examined by the use of a three-dimensional force sensor under the experimental conditions similar to the present study.

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