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Roles of proximal-to-distal sequential organization of the upper limb segments in striking the keys by expert pianists

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Abstract

Roles played by the proximal-to-distal sequencing (PDS) of the multi-joint limb in a relatively slow target-aiming task by the arm were investigated using keystroke motion on the piano. Kinematic recordings were made while experts ($N=7$) and novices ($N=7$) of piano players performed an octave keystroke at four linearly-scaled loudness levels with a short tone production (*staccato*) technique. The temporal relationship of the peak angular velocity at the shoulder, elbow and wrist joints showed a clear PDS organization for the experts, but not for the novices. The result thus confirmed that the PDS occurred in a slow and skilled multi-joint movement. The summation effect of segmental speed in terms of increment of the peak segmental angular velocity was equal for both groups. Similarly, no group difference was found for the total kinetic energy produced by the upper limb during keystroke. The role of the PDS in piano keystroke thus cannot be explained by the exploitation of speed-summation effect and mechanical efficiency. Compared to the novices, the experts had a longer period and a greater magnitude of deceleration at the shoulder and elbow joints while their adjacent distal joints were accelerating. These results indicated that greater inertial forces had been generated to descend the forearm as well as the hand for the experts. A dominant role of the PDS in pianists can therefore be to effectively exploit motion-dependent interaction torques at the forearm and hand, and thereby reducing muscle-dependent torques to make the keystroke more physiologically efficient.

Keywords: Motor control; Motor learning; Multi-joint movement; Interaction torque

Keystrokes on the piano commonly start with lifting the arm to some height, dropping it for the finger(s) to hit and depress the target key(s), and lifting the hand again to release the key depression. The production of an aimed sound requires precisely regulated key-depression velocity of the hand, the endpoint segment of the dropping arm. One of the most fundamental temporal and spatial features describing a well-coordinated motion of the linked-segments such as the arm may be the appearance of a proximal-to-distal sequencing (PDS) pattern [12–14]. There, the timing of movement onset for the moving joints as well as the segments was arranged in the order from the proximal to distal. PDS organization of the upper limb has been commonly recognized while throwing a ball performed by a skilled subject (e.g., [4,13]). Some merits of the PDS organization have also been argued [2,12,13]. These include, the effective use of speed-summation, and control of motion-dependent joint force, the so-called interaction torque [6–8,12,13]. The extent of receiving these advantageous effects may depend on the nature of motor action, such as movement speed and its accuracy, required spatial accuracy, range of joint motion, relative angle of the segments, object mass as well as external force acting on the object manipulated, and the level of the performer's expertise [13,14].

Although much has been studied about these issues on the upper limb motion for throwing a ball (see reviews by [15]), little has been investigated on the piano keystroke [3,10]. The piano keystroke differs from a ball-throw in many respects which are thought to be characteristic of PDS organization, including the use of a much slower and a narrower range of hand velocity, a higher accuracy demand in key-contacting velocity of the hand, a higher spatial accuracy demand to hit the 2-cm wide key, a requirement for control of key-reaction force, and the presence of a follow-through arm lift (a reversal motion from key depression) after the collision. These features infer the difficulty of the PDS organization in the piano keystroke. However, our preliminary study of upper limb kinematics in pianists suggested the use of PDS for keystroke motion [3]. The findings from an early study

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by Bernstein and Popova [10] also suggested that well-trained pianists utilized interaction force between the forearm and hand at fast rhythmic keystrokes.

The present study attempts to clarify our earlier finding concerning the PDS organization in piano keystroke by taking the level of player's skill, and the end point (the hand) movement velocity for the regulation of sound loudness into consideration. The purposes of the present study were, therefore, to determine if unimanual arm motion for an octave keystroke performed by expert and novice piano players was organized in PDS when producing different levels of piano sound, and to examine the relation with the advantageous effects of the PDS organization in piano keystroke.

Seven active expert pianists (3 males and 4 females, mean age ± S.D. = 24.3 ± 3.2 years.) with more than 15 years of classical piano training, and seven novice piano players (3 males and 4 females, age = 21.0 ± 4.6 years.) with less than a year of piano training served as participants in the present study. All participants were right-handed. Informed consent was obtained from all participants, and the study was approved by the ethics committee at Osaka University.

The experimental apparatus used were an upright piano, two 2-D position sensor systems (C5949, Hamamatsu Photonics Co. Japan), a sound-level meter (NA-27, Rion Co. Japan), and a stereo sound amplifier. The sound-level meter placed 1 m above the keyboard collected sound signal at sampling frequency of 900 Hz. The experimental task was a right-hand octave keystroke, a simultaneous strike of the 35th (G3) key by the thumb and the 47th (G4) key by the little finger. The keys were 166 mm apart. Simple one-hand octave keystroke was chosen to induce a whole arm movement, as well as to keep mediolateral deviation of the hand and arm during keystroke less than 8 mm and long-axis rotation (pronation/supination) of the forearm less than 0.07 rad to permit a 2-D kinematic analysis [3]. In the experiment, the participant started with lightly touching the fingertips of the right hand on the keys, lifted his/her right arm/hand to a self-determined height at a self-determined speed, stroked the keys in a short tone production (a *staccato* touch) at a designated level of tone, lifted the hand and arm again as a follow-through to a self-determined height, and returned to the initial position. The left arm and hand were kept relaxed and placed on the side of the trunk while the trunk was in an upright position with minimum movement.

Based on our previous studies, four target sound pressure levels (SPLs) of 103, 106.5, 110, and 113.5 dB were chosen in this study, which roughly corresponded to loudness for a *piano* (*p*), mezzo-*piano* (*mp*), mezzo-*forte* (*mf*), and *forte* (*f*), respectively [3]. Kinematic and simultaneous sound data were collected from 30 successful strokes at each of the target SPLs with an approximately 10-s trial-to-trial interval per stroke for each participant. The target SPL was a pre-recorded piano sound on the MiniDisc, which was presented from a set of speakers placed on the top of the piano. With the help of the experimenter providing feedback about the difference in the produced and given SPLs, each participant practiced the task until he/she could reduce the error to within above or below 0.9 dB of the target SPL before the data collection.

Movement of the upper limb and trunk in the sagittal plane was recorded using one of the position sensor cameras (sampling freq. = 150 Hz) located at 3.5 m on the right side from the participant. The LEDs for this were mounted on the skin over the carefully estimated centers of the metacarpo-phalangeal (hand), styloid process (wrist), head of radius (elbow), coracoid process (shoulder), and greater trochanter (hip) joints. Prior to the experiment, the accuracy of these LED positions was always checked visually using a video recorder. The data were digitally smoothed at the cut-off frequency of 10 Hz using a second-order Butterworth digital filter. Angular displacement at the wrist, elbow and shoulder joints was then numerically calculated using an inner product method, and linear and angular velocities were calculated using a numerical differentiation method.

The G3-key kinematics was recorded using another position sensor camera located 0.65 m left from the key, and an LED placed on the key surface. Onset of key descending movement ("the finger-key contact moment") was determined when the calculated vertical velocity of the key exceeded 5% of its peak velocity. Movement of the G4 key was not measured due to difficulty in placing a close-up view camera in the right side of the piano without interfering with the kinematic recording of the hand movement by the other far view camera. In a pretest of octave keystrokes performed at varied loudness levels, a significant spatio-temporal synchrony of the G3 and G4 keys had been confirmed ($r > 0.76$).

Temporal and kinematic variables were computed from the data at each keystroke trial. Representative angular velocity curves of the shoulder, elbow, and wrist joints during the entire period of keystroke motion including the follow-through-upswing at the *f* and *p* loudness levels in one expert and novice are shown in Fig. 1A. The temporal variables evaluated were the durations between the moments of peak angular velocity at the wrist, elbow and shoulder joints (see circles in Fig. 1A) and the lowest key position (see a dotted vertical line in Fig. 1A), and the duration of keystroke defined as the period from the moment of the highest hand position (see the arrows in Hand of Fig. 1A) to the moment of the lowest key position. In addition, by computing the difference in the time of peak angular velocity from the proximal joint to the adjacent distal joint, the period in which the proximal joint is in deceleration while the distal joint is in acceleration was assessed. This was used to evaluate the period in which interaction torques helped in the rotation at the distal joint(s). The kinematic variables were the peaks of the linear vertical velocities of the hand (metacarpo-phalangeal) joint, the peaks of the segmental angular velocities of the hand, forearm and upper-arm, and the peaks of the angular velocities and decelerations at the wrist, elbow and shoulder joints. Using the equations given below, kinetic energy of the whole upper limb from the onset of keystroke to the moment of the finger-key contact was also computed:

$$\mathrm{KE}_{\mathrm{segment}\,(i)} = \frac{1}{2}m_i v_i^2 + \frac{1}{2}I_i\omega_i^2$$

$$\text{Total KE} = \sum_{1}^{3}\mathrm{KE}_{\mathrm{segment}\,(i)}$$

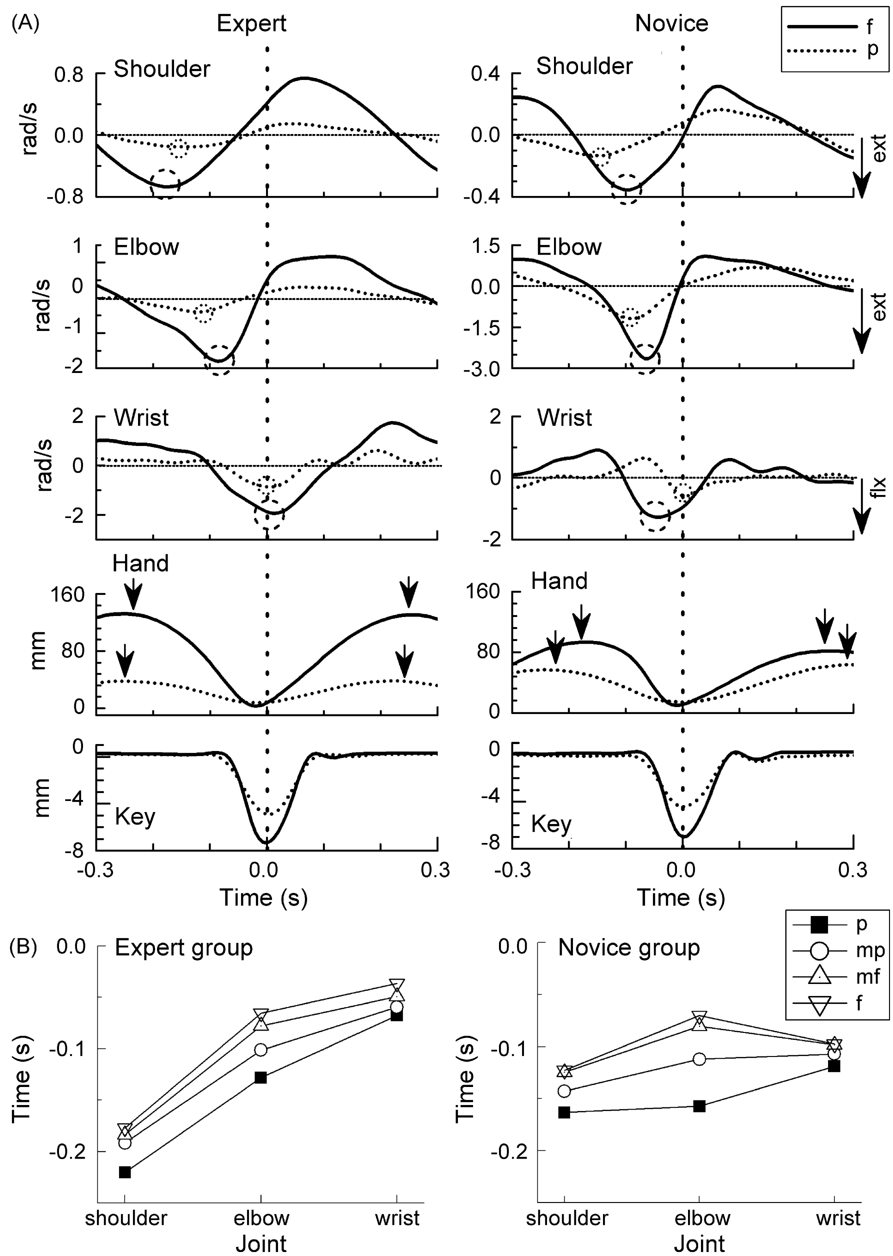

Fig. 1. The time-history curves of wrist, elbow, and shoulder joint angular velocities, and their corresponding hand and key vertical displacements at *f* and *p* loudness levels in one representative expert and novice pianists (A). The curves represent the average of 30 keystrokes. The arrows indicate the moments of the maximum hand position; for the onset of keystroke and for the end of upswing. The dotted line indicates the moment of the lowest key position, when the keystroke ended. The circles indicate the moments of peak joint angular velocity. The mean values of the occurrence times at the peak angular velocities for the wrist, elbow, and shoulder joints for each of the expert and novice groups (B).

where m_i = mass of the ith segment (i = 1, 2, 3; upper-arm, forearm, hand), v_i = velocity of the center of mass of the ith segment, ω_i = angular velocity of the ith segment, and I_i = moment of inertia of the ith segment about its center of mass. The measured data and body segment parameters for Japanese were used for these computations [1].

Statistical tests were performed using a two-way or three-way ANOVA with repeated measures. All statistical significance was set at $p < 0.05$.

The mean durations of the keystroke at the *p*, *mp*, *mf*, and *f* loudness levels for the experts were 344 ± 69, 312 ± 69, 289 ± 71, and 272 ± 57 ms, respectively. The corresponding means for the novices were 328 ± 125, 296 ± 99, 268 ± 80, and 272 ± 79 ms, respectively. ANOVA revealed a significant loudness effect ($F(3, 36) = 23.3$, $p < 0.01$), but not for the effects of group and group × loudness interaction. The mean values of the peak hand descending velocity (segmental-endpoint velocity in this study) at these loudness levels were 291.4 ± 33.1, 385.2 ± 40.5, 621.1 ± 64.0, and 771.9 ± 72.3 mm/s, respectively, for the expert group, and 362.3 ± 40.6, 463.7 ± 37.0, 604.0 ± 36.2, and 793.9 ± 75.2 mm/s, respectively, for the novice group. There was again a significant effect only for loudness ($F(3, 36) = 36.9$, $p < 0.01$).

During keystroke, the summation effect of angular velocity from the shoulder to the elbow, and the elbow to the wrist can be observed in the curves of the expert player (see circles in the left panel of Fig. 1A). That is, elbow extension velocity started to develop just before shoulder extension velocity reached its peak, and it reached the peak as the shoulder extension velocity ended. Likewise, wrist flexion velocity began when elbow velocity reached its peak, and ended at the occurrence of peak wrist velocity. There was, therefore, a clear ordinal relation in the occurrence of peak angular velocity for the shoulder, elbow and wrist joints in the expert at both loudness levels (see circles in the left panel of Fig. 1A). For the novice, on the other hand, such temporal organization was less clear (circles in the right panel of Fig. 1A). Results of other participants were similar to these examples.

The mean values of the peak occurrence time, therefore, clearly showed an ordinal relationship in the timing of peak angular velocity among three joints for the expert group but not for the novice group (Fig. 1B). Three-way ANOVA revealed a significant group × joint effect ($F(6, 72) = 2.9$, $p < 0.05$) while the group × joint × loudness interaction effect was not significant. To examine if the timing differences among all three joints were significant, Tukey *post hoc* tests were further performed within each group data. It was found that at all loudness levels the timing differences among all three joints were significant for the experts ($p < 0.05$) but not for the novices.

To assess whether the experts took a greater advantage of the speed-summation effect, the increment of peak segmental angular velocity from the upper arm to the forearm (Fig. 2A), and that from the forearm to the hand (Fig. 2B) were computed at all loudness levels. These incremental values, which increased with loudness, were similar between the two groups. ANOVA revealed a significant effect of loudness (upper-arm to forearm: $F(3,36) = 30.62$, $p < 0.01$; forearm to hand: $F(3,36) = 4.19$, $p < 0.05$), but neither the loudness × group interaction effect nor the group effect was significant, confirming no difference in speed-summation between the experts and novices.

Kinetic energy generated to strike the keys by the upper limb was computed to compare mechanical efficiency of keystroke between the two groups. The mean values of the increase in a total kinetic energy during keystroke at the *p*, *mp*, *mf*, and *f* loudness levels for the experts were 57 ± 39, 94 ± 38, 206 ± 108, and 317 ± 170 mJ, respectively. The corresponding means for the novices were 71 ± 37, 98 ± 41, 150 ± 48, and 279 ± 157 mJ, respectively. ANOVA confirmed no group difference in total kinetic energy used for keystroke.

If, as expected from the findings of the previous studies [4,8], motion-dependent interaction torques are exploited more to accelerate the distal joint rotation for the experts than the novices, the experts would show (1) a longer duration of the period in which the proximal joint rotation is decelerating while the adjacent distal joint rotation is accelerating and (2) greater peak angular deceleration at the proximal joints than the novices. The mean values of the duration, in which the shoulder extension was decelerating while the elbow extension was accelerating (Fig. 2C), and in which the elbow extension was decelerating while the wrist flexion was accelerating (Fig. 2D), were all positive for the experts, whereas those for the novices were fairly small or sometimes negative. ANOVA revealed a significant group effect for each of these values (the shoulder to the elbow: $F(1, 12) = 6.1$, $p < 0.05$; the elbow to the wrist: $F(1, 12) = 12.9$, $p < 0.01$). The mean values of the magnitude of peak angular deceleration for shoulder extension (Fig. 2E) and elbow extension (Fig. 2F) were also computed at all loudness levels. For the shoulder, ANOVA revealed a significant interaction effect of group × loudness ($F(3, 36) = 26.1$, $p < 0.01$) and main effect of group ($F(1, 12) = 13.1$, $p < 0.05$). The results indicated that a larger shoulder deceleration occurred for the experts than the novices, and this difference was larger at louder sound generation. For the elbow, ANOVA revealed no group-related effects.

For the experts and novices, the peak velocity of the hand used for sound production on the piano ranged from 0.3 m/s to 0.8 m/s, which was only one-tenth of those reported for throwing a baseball (5.4–11.4 m/s; [6], 20–26 m/s; [7]). A novel finding of the present study was that despite the slowness of the upper limb motion for striking the keys, there was a clear temporal relationship from the shoulder-to-elbow, and the elbow-to-wrist joints for the experts. The results thus indicate that the PDS organization plays some role in the execution of a relatively slow target-aiming multi-joint movement. Because the novices did not show such temporal organization at any loudness level, training would be essential for its establishment. This, however, seems to agree with the findings of the previous study in which ball-throw movement was organized in PDS for the dominant-arm but not for the non-dominant arm [4].

As a merit of PDS, a summing effect of segmental speed has often been discussed [2,13]. The speed-summation effect indicates that to produce the highest speed at the end of a linked-chain of segments, the motion should start with the more proximal segment and proceed to the more distal one, with the more distal segment beginning its motion at the time of the maximum speed of the proximal one, with each succeeding segment generating a larger rotational speed than the proximal segment. We can apply this to keystroke for the production of a target piano sound. For a well-organized PDS motion of the upper-limb in expert pianists, increments or carry-over effects of rotational velocity from the proximal to distal segments could be maximized, and thus the amount of such increments were expected to be greater for the experts than the novices.

At a given rotational velocity of the end-point segments for keystroke to meet the required sound level production, we can then expect to find a smaller amount of angular velocity at the associated joints for the experts than the novices. In addition, because smaller joint angular velocity requires less mechanical work by joint torque, the magnitude of mechanical (kinetic) energy required for moving the whole arm for a keystroke could also be less for the experts than the novices. Studies have indeed shown that energetic efficiency to reach some targets using the whole upper limb improved with extensive training (e.g., [11]). Contrary to our expectation, however, the present findings indicated that neither the increment values of segmental angular velocity nor the total kinetic energy of the arm was

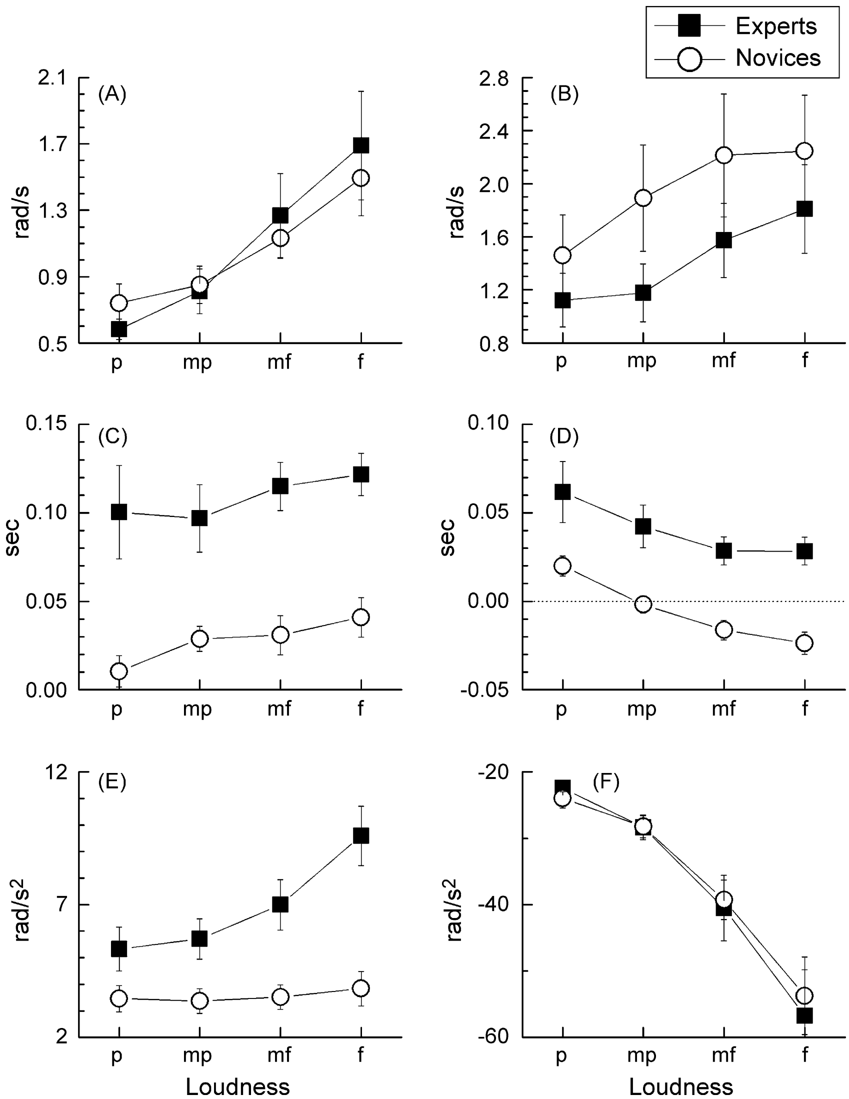

Fig. 2. The group difference in the mean increment of the peak segmental angular velocity from the upper arm to forearm (A) at all loudness levels, and those from the forearm to the hand (B), the group differences in the mean duration of period in which the shoulder extension was in deceleration while the elbow extension was in acceleration (C) at all loudness levels, and those in which the elbow extension was in deceleration while the wrist flexion was in acceleration (D), and the group differences in the mean peak angular deceleration for the shoulder joint (E), and the elbow joint (F). Error bars represent ±1 S.E.

different between the experts and novices. Therefore, the speed-summation and associated mechanical efficiency does not seem to explain the merits of organizing the limb motion in PDS observed for the experts.

Another merit of PDS is an exploitation of interaction torques, rotational forces that arise at one joint because of motion in the limb segments about other joints [6,8,13]. Hirashima et al. [6] have shown that during throwing a ball, a thrower intentionally decelerates the upper-arm rotation toward the end of the throwing action, which generates interaction torques at the elbow joint. This passive torque helped in the muscle-dependent torque at the elbow to propel the forearm. Since the interaction torques stem only from movements of the segments, for the performers to be able to exploit those appropriately, both the timing and magnitude of upcoming interaction torques have to be precisely predicted before the actual motor action takes place. A PDS organization in which timing and magnitude of joint angular acceleration for the moving limb are appropriately incorporated is therefore essential for the skilled performance of the multi-joint movement [9]. The fact that the PDS organization of the upper limb movement was not found in novices suggested that they did not or could not utilize the resulting interaction torques effectively in their keystroke motion. For the experts, on the other hand, a clear PDS pattern with the temporal relation having a period in which shoulder extension was decelerating while elbow extension was accelerating (Fig. 2A), followed by another period in which elbow extension was decelerating while wrist flexion was accelerating (Fig. 2B) was observed. We also confirmed a substantial magnitude of deceleration of shoulder extension, which was also movement-speed dependent, for the experts (Fig. 2C). These findings indicate that the PDS organization in expert players is linked predominately to the exploitation of interaction torques efficiently to propel the forearm and hand at an intended velocity for keystroke. This may agree with the finding of an early study by Bernstein and Popova [10] who reported that the expert pianists move their limb in a forced elastic oscillation mode to accelerate their hands when striking the keys at faster tempi.

Theoretically, the total kinetic energy is generated as the sum of works made by the gravitational, interaction, and muscular torques at the moving joints [6]. Our findings strongly suggest that the experts are exploiting interaction torques effectively through the PDS organization of the limb while the novices are not. Consequently, no difference in the total kinetic energy of the arm during keystroke between the experts and novices implies that muscular and/or gravitational torques is less in the experts compared to the novices. Computation of these joint torques during the present motor task is, unfortunately, a complex kinetic problem due to the presence of key-reaction force at the end of the keystroke. The earlier work by Bernstein and Popova [10] indicated that the effective use of gravitational force to reduce muscular effort for striking the keys was quite limited even by the expert pianists. It is then possible to postulate that muscular torques required for keystroke of the experts has been reduced, making the limb movement physiologically more efficient.

Reasons for the lack of PDS in novices can be extended beyond utilization of its merits. One of those may be the adoption a limb stiffening strategy or "freezing" of degrees of freedom [15], in relation to movement error reduction. In a test of reaching toward varied sizes of a target, Gribble et al. [5] have shown that the subjects used greater coactivation of the agonist and antagonist pairs of the shoulder and elbow muscles for a smaller target size. They have also shown that the level of cocontraction gradually decreased with practice trials. A similar line of evidence has been provided for the task of arm movement under different force fields [12]. Southard [14] earlier reported that in a task of striking a ball on a tee using the hand, learners who were instructed to perform the task as fast as possible acquired the PDS organization of segmental motions by the end of 5 days practice session. However, those who emphasized accuracy of the ball placement did not acquire the PDS segmental motion. These findings suggested that stiffening the joints is one strategy and thus the multi-joint limb moves as if a uni-joint limb for the motor system to facilitate movement accuracy at an early stage of learning a motor task. This may be the case in our novice players, although it is energetically expensive.

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