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Individual differences in the biomechanical effect of loudness and tempo on upper-limb movements during repetitive piano keystrokes

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ABSTRACT

The present study addressed the effect of loudness and tempo on kinematics and muscular activities of the upper extremity during repetitive piano keystrokes. Eighteen pianists with professional music education struck two keys simultaneously and repetitively with a combination of four loudness levels and four tempi. The results demonstrated a significant interaction effect of loudness and tempo on peak angular velocity for the shoulder, elbow, wrist and finger joints, mean muscular activity for the corresponding flexors and extensors, and their co-activation level. The interaction effect indicated greater increases with tempo when eliciting louder tones for all joints and muscles except for the elbow velocity showing a greater decrease with tempo. Multiple-regression analysis and *K*-means clustering further revealed that 18 pianists were categorized into three clusters with different interaction effects on joint kinematics. These clusters were characterized by either an elbow-velocity decrease and a finger-velocity increase, a finger-velocity decrease with increases in shoulder and wrist velocities, or a large elbow-velocity decrease with a shoulder-velocity increase when increasing both loudness and tempo. Furthermore, the muscular load considerably differed across the clusters. These findings provide information to determine muscles with the

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greatest potential risk of playing-related disorders based on movement characteristics of individual pianists.

1. Introduction

Playing-related musculoskeletal disorders (PRMD's) have long been prevalent among pianists. Survey studies have reported that more than 60% of piano players and teachers have suffered from this occupational disorder ranging from acute pain to more serious problems, such as tendonitis, carpal tunnel syndrome, and focal dystonia (Bragge, Bialocerkowski, & McMeeken, 2006; Bruno, Lorusso, & L'Abbate, 2008; Furuya, Nakahara, Aoki, & Kinoshita, 2006; Jabusch, Vauth, & Altenmüller, 2004). Several studies also have attempted to qualitatively determine their risk factors, which included age, sex, practice duration, and anthropometric features of the hand (De Smet, Ghyselen, & Lysens, 1998; Furuya et al., 2006; Farias et al., 2002; Revak, 1989). In contrast, biomechanical factors that influence the physiological load at the upper-extremity muscles during piano playing have been not fully addressed, which has limited prevention, diagnosis, and treatment of PRMD's.

Loudness and tempo are fundamental musical variables that crucially influence the muscular load on the upper extremity during piano playing. Our previous study examined the effect of the loudness of a tone on the force applied to the fingertip during the keystroke (Kinoshita, Furuya, Aoki, & Altenmüller, 2007). The results demonstrated an exponential increase in the key-force with loudness. More recently, a series of our biomechanical studies found an increase in the magnitude of agonist–antagonist muscular co-activation, muscular torque, and kinetic energy at the upper extremity in proportion to loudness (Furuya & Kinoshita, 2007, 2008a, 2008b; Furuya, Osu, & Kinoshita, 2009; Furuya, Altenmüller, Katayose, & Kinoshita, 2010). In addition, the increases in co-activation and muscular torque with loudness were less pronounced for the expert pianists as compared to the novice piano players, which highlighted expertise-dependent differences in the muscular load during piano keystroke.

One limitation of these previous studies on the biomechanics of piano keystroke is that neither the effect of tempo nor the interaction of tempo and loudness on the kinematics and muscular activities of the upper extremity was investigated, because they only focused on a discrete piano keystroke. The information on the interaction of tempo and loudness is particularly important for determining muscles with the greatest potential risks of PRMD's during piano playing, since the muscular load should drastically increase when striking both stronger and faster (i.e., increasing both loudness and tempo). Another limitation is that none of the previous studies probed into individual differences in physiological load at the upper-extremity muscles. Due to the redundant number of joints and muscles, our motor system is capable of accomplishing a particular task goal with different movement organizations. It is thus reasonable to assume that the muscular load during piano playing would differ across pianists. To characterize it through examining a large number of players is indispensable because clinical and epidemiologic studies reported that the body portion with symptoms of PRMD's differed cosiderably across pianists (Bragge et al., 2006; Bruno, Lorusso, & L'Abbate, 2008; Furuya et al., 2006).

The primary purpose of the present study is to assess the biomechanical effect of loudness and tempo on repetitive piano key-striking movements. Our specific focus is on the interaction of these variables on movement kinematics and muscular activities. We postulate that changes in joint velocity and muscular activities in relation to loudness differ depending on tempo. The secondary purpose of the study is to evaluate the relationships between individual differences in the interaction effect on joint kinematics across pianists and the muscular load on the upper extremity. To this aim, we collected data from 18 pianists. We hypothesized that there should be a small number of representative kinematic strategies to strike stronger and faster; we also hypothesized that the muscular load should differ across these strategies. We tested them quantitatively using multiple-regression analysis and clustering analysis.

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2. Methods

2.1. Participants

Eighteen right-handed pianists (5 males and 13 females, 30.2 ± 7.8 years old) with more than 15 years of classical piano training participated in the study. All pianists were studying at or had graduated from a music conservatory. In accordance with the Declaration of Helsinki, the experimental procedure was explained to all subjects and each subject signed a written informed consent. The study was approved by the local ethics committee of Osaka University.

2.2. Experimental apparatus and key-striking task

The experimental apparatus consisted of a Yamaha U1 upright-piano, an 8-channel telemetric electromyography (EMG) system (Nihon Koden Co.), and two 2-D position sensor systems (Hamamatsu Photonics Co.). A strain-gauge miniature uniaxial force transducer was installed at the C5-key at its distal end, which was sampled at 900 Hz. The experimental task was right-hand repetitive and simultaneous keystrokes of the 44th (E4) key by the thumb and the 52nd (C5) key by the little finger (i.e., major sixth chord). We used the chord task primarily for three reasons. First, our previous questionnaire study revealed that the pianists who were experiencing excessive muscle tension when playing chords had a higher rate of PRMD's at the upper extremity (Furuya et al., 2006), which implicates that the chord task is physically demanding. Second, most of our previous studies investigated the upper-extremity movements during striking two keys simultaneously in order to minimize the medio-lateral and pronation-supination movements of the hand and arm, as confirmed before (Furuya & Kinoshita, 2008a; also, a significant spatio-temporal synchrony of the two struck keys had been previously confirmed by Furuya and Kinoshita (2007)). Third, repetitive keystroke of a single key is not commonly used in piano pieces, whereas a lot of piano pieces require simultaneously striking two keys repetitively (e.g., pieces composed by Liszt, Rachmaninoff).

The subject was asked to strike the keys for short tone production ("*staccato*") for 30 strokes at a designated tone loudness and striking tempo in randomized order. The four loudness levels of piano (*p*), mezzo-piano (*mp*), mezzo-forte (*mf*), and forte (*f*) were selected in this study, which corresponded to strokes with maximum key-forces of 1.5, 2.7, 3.9, and 5.1 N, respectively. In the present study, we defined the loudness as dynamic level (= key-force) instead of the dB value of elicited tones, because our experiment was performed in an ordinary rather than a sound-proof room. The piano tone elicited by a keystroke with the target force (= *p*, *mp*, *mf*, and *f*) was pre-recorded before the experiment by a pianist who did not participate in the present study; this sound was presented from a set of speakers placed on top of the piano to provide each subject with information on the target loudness. After each experimental trial consisting of 30 successive strokes, the experimenter computed the key-force averaged within the trial. The subject was asked for a retrial by the experimenter when the mean recorded key-force was greater or smaller by more than 20% of the target force compared with the target key-force. The striking tempi were 3, 4, 5, and 6 Hz (= 180, 240, 300, and 360 beats per minutes, respectively), and the tempi were provided by a metronome before each trial.

2.3. Data acquisition

The upper-limb movement in the sagittal plane was recorded at 300 Hz using one of the position sensor cameras. The LED's were mounted on the skin over the fingertip of the little finger and at the centers of the metacarpo-phalangeal (finger), the styloid process (wrist), the head of the radius (elbow), and the coracoid process (shoulder) joints. The E4-key kinematics was also recorded using another camera and an LED placed on the key surface. The data were digitally smoothed at a cut-off frequency of 12 Hz using a second-order Butterworth digital filter.

The electrical activities of the right side of the anterior and posterior deltoids (AD and PD), triceps brachii, biceps brachii, flexor digitorum superficialis (FDS), and extensor digitorum communis (EDC) muscles were recorded with a surface EMG system. Pairs of Ag/AgCl disposable electrodes were placed at the estimated center of the belly of each target muscle. The EMG signals were amplified (×5000) and sampled at 900 Hz. The signals were digitally high-pass filtered with a cut-off frequency of 20 Hz and then root-mean-squared. The background noise was removed by subtracting the mean activity of each muscle while the arm and hand were relaxed. To normalize these EMG data for each muscle for each subject, maximum voluntary contraction (MVC) EMG data were obtained for each muscle by asking the subject to perform maximum flexion or extension isometric force production against a stationary object, at a designated joint angle for a 5-s period. Details of this procedure have been mentioned elsewhere (Furuya & Kinoshita, 2008a). Using the mean value of the middle 3-s period of the MVC data, a percentage MVC value was calculated.

2.4. Data analysis

During each period between successive keystrokes: (1) the peak angular velocity for shoulder flexion, elbow extension, wrist flexion and finger flexion, (2) the mean activity of the six measured muscles, and (3) the co-activation index (CI) of the forearm, upper-arm, and shoulder were computed. The CI was used to evaluate the amount of co-activation of the agonist and antagonist muscles. Based on previous studies (Furuya & Kinoshita, 2008a; Kellis, Arabatzi, & Papadopoulos, 2003), we computed the CI as follows:

$$\mathrm{CI} = \left(\int_{t1}^{t2} EMG_{agon}(t)dt + \int_{t2}^{t3} EMG_{ant}(t)dt \right) / \Delta T$$

where the period from $t1$ to $t2$ denotes the time when the agonist EMG activity is less than the antagonist EMG, and vice versa for the period from $t2$ to $t3$. ΔT is the inter-keystroke interval.

Each of the kinematic and EMG variables was averaged across 30 strokes. To evaluate individual differences in the interaction effect of loudness and tempo on joint kinematics and muscular activity, multiple-regression analysis was performed for one of these three variables for each pianist, i.e.,

$$Y = a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_1 \cdot X_2 + b$$

where Y is one of the kinematic and EMG variables at a particular joint/muscle; X_1 is the tempo (3, 4, 5, 6 Hz); X_2 is the loudness (1.5, 2.7, 3.9, 5.1 N); a_1, a_2, and a_3 are standardized partial regression coefficients; and b is the intercept coefficient. Note that this model includes a term that reflects the interaction effect between loudness and tempo ($X_1 \cdot X_2$).

To assess the similarity of the interaction effect on joint kinematics across pianists, K-means clustering analysis was performed using the derived regression coefficients for interaction effect (i.e., a_3) on the peak velocity of all joints for all subjects. Here, the peak velocity at all joints for each subject was represented as a point in the four-dimensional hyperspace. K-means analysis determines the inter-subject similarity based on the proximity of the points. The K value used in the study was 2, 3, or 4, which corresponded to the number of clusters. To determine the K value with the least error, the silhouette value was computed (Rousseeuw, 1987). If the silhouette value is close to 1, it means that the sample has been assigned to an appropriate cluster. If the silhouette value is close to -1, however, it means that the sample is misclassified. We therefore reasoned that the mean silhouette value across subjects should be largest at the optimal K value.

For each cluster, the mean values of the coefficient related to the interaction effect on mean muscular activity and CI across subjects were computed. By comparing them across clusters, we evaluated whether muscular load differed depending on kinematic variation when striking both stronger and faster.

2.5. Statistics

Using loudness and tempo as independent variables, a two-way ANOVA with repeated measurements was performed for each of the dependent variables ($p < .05$).

3. Results

3.1. Time-course of kinematics and muscular activities

Fig. 1 shows profiles of the activities at the flexor and extensor muscles and joint angular velocity of the upper limb, and vertical position of the finger-tip and key across different tempi (3 and 6 Hz) and

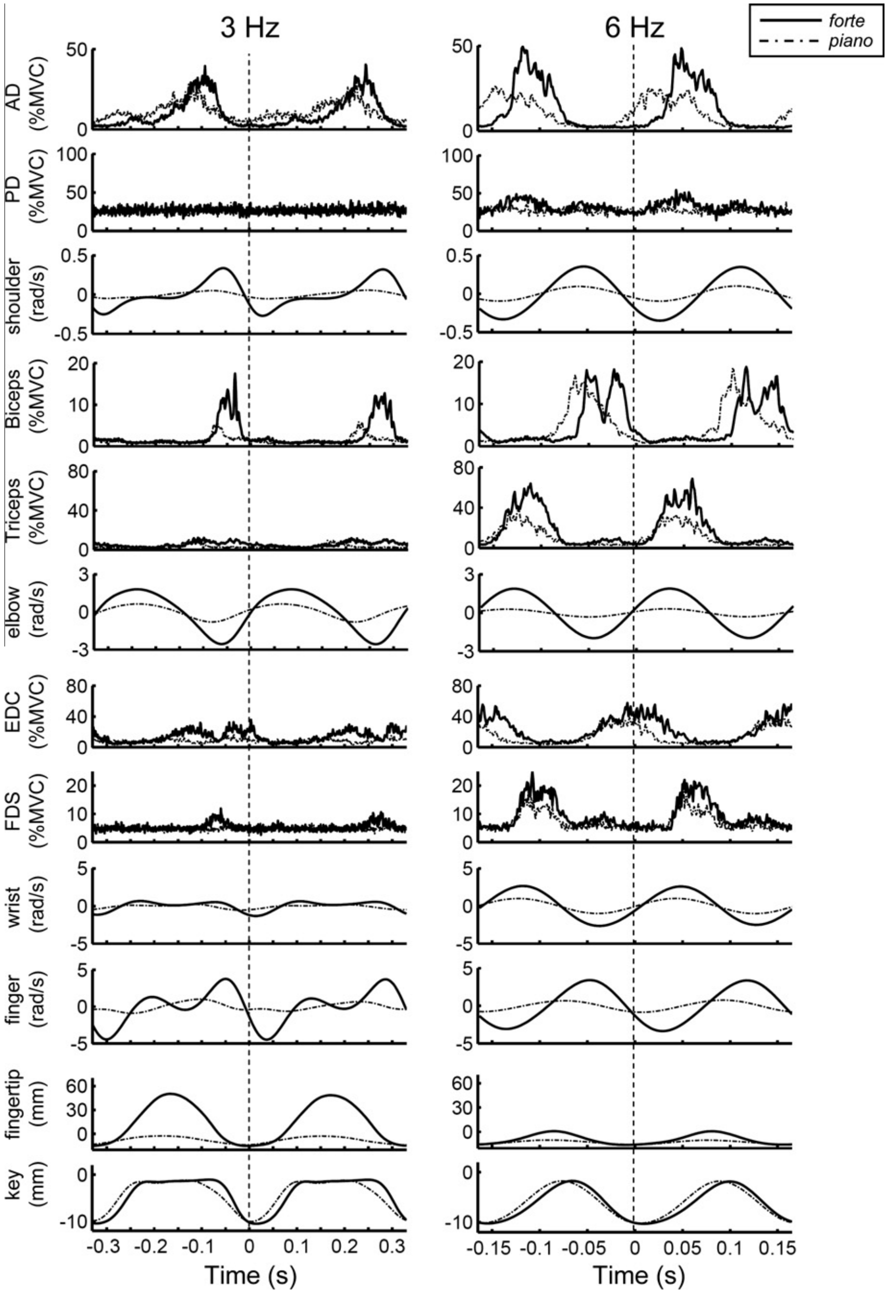

Fig. 1. The time-history curves of the activities at the shoulder flexor (AD) and extensor (PD) muscles, shoulder angular velocity, activities at the elbow flexor (biceps) and extensor (triceps) muscles, elbow angular velocity, activities at the wrist and finger extensor (EDC) and flexor (FDS) muscles, wrist and finger angular velocity, and vertical position of the fingertip and key across different tempi (3 and 6 Hz) and loudness (*piano* and *forte*) for one representative pianist. The curves represent the average of 30 keystrokes. The solid and dashed lines represent the loudness of *piano* and *forte*, respectively. The time of zero represents the moment where the key is at its lowest position, which is denoted by a vertical dotted line.

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loudness (*piano* and *forte*) for one representative pianist. The figure indicates that the shoulder flexion velocity was prominent during the descent of the fingertip to depress the key at *forte* dynamics for both fast and slow tempi ("shoulder" in Fig. 1). The joint velocity and the activity at both the AD and PD muscles showed greater amplitude for louder tones and faster tempi ("AD" and "PD" in Fig. 1). In addition, the activity of these muscles increased with loudness even more strongly at faster tempi. Note that half of our subjects showed less activity in the shoulder extensor muscles when striking at slow tempo.

The elbow extension velocity started to increase when the fingertip descent was initiated and reached its peak around the moment of the key-press, irrespective of tempo and loudness ("elbow" in Fig. 1). The magnitude of elbow velocity was greater for louder tones but smaller at faster tempi. While the activities of the biceps and triceps muscles occurred simultaneously at the slow tempo, they became reciprocal at the fast tempo ("Biceps" and "Triceps" in Fig. 1). The biceps activity became greater for louder tones and faster tempi, whereas the triceps activity was fairly small and unclear at the slow tempo but became substantial at the fast tempo.

During key depression, flexion and extension velocities were generated for the wrist and finger joints, respectively ("wrist" and "finger" in Fig. 1). The amplitude of these velocities became greater at louder tones and faster tempi. The EDC and FDS muscles were active simultaneously at the slow tempo, whereas their activity was reciprocal at the fast tempo ("EDC" and "FDS" in Fig. 1).

3.2. Peak angular velocity

Fig. 2 shows the mean peak angular velocities at the shoulder, elbow, wrist, and finger across subjects at different loudness and tempi. For all joints, the velocity became greater with increased loudness. The velocity was also increased with increasing tempo for the shoulder and wrist but decreased for the elbow. These changes with tempo became stronger for louder tones. With an increase in tempo, the finger velocity decreased for quieter tones and increased for louder tones. ANOVA confirmed a significant interaction effect for all joints (Table 1). There were also main effects of loudness and tempo for all joints except for the tempo effect on finger velocity.

3.3. Mean EMG activity

Fig. 3 shows the mean activities for all measured muscles across subjects at different loudness and tempi. For all of these muscles, the value was increased with increased loudness and tempo. ANOVA confirmed a significant Loudness $\times$ Tempo interaction for all muscles (Table 1), indicating a greater increase with tempo at louder tones. There were also main effects of loudness and tempo for all muscles.

3.4. Co-activation index (CI)

Fig. 4 shows the mean CI values for the shoulder, upper-arm, and forearm muscles. In all of these muscles, the value increased with both loudness and tempo. ANOVA showed a significant Loudness $\times$ Tempo interaction effect, indicating a greater increase with tempo at louder tones (Table 1). Also, the main effects of both loudness and tempo were significant for all muscles.

3.5. Multiple-regression analysis and K-means clustering

The multiple-regression coefficients for all subjects when predicting the interaction between loudness and tempo on the peak angular velocity and the results of K-means clustering are listed in Table 2. The mean silhouette values when K was 2, 3, and 4 were .40 ± .22, .49 ± .09, and .51 ± .17, respectively, which indicates that splitting the data into four clouds gave the least error. However, when $K = 4$, one of the four clusters had only one subject. Because there was no significance difference in silhouette values between $K = 3$ and 4 (t-test: $p = .72$), we adopted $K = 3$ in subsequent analyses.

The K-means showed that 12 subjects were categorized into cluster 1, whereas clusters 2 and 3 had three subjects each. Cluster 1 was primarily characterized by negative and positive coefficients for the

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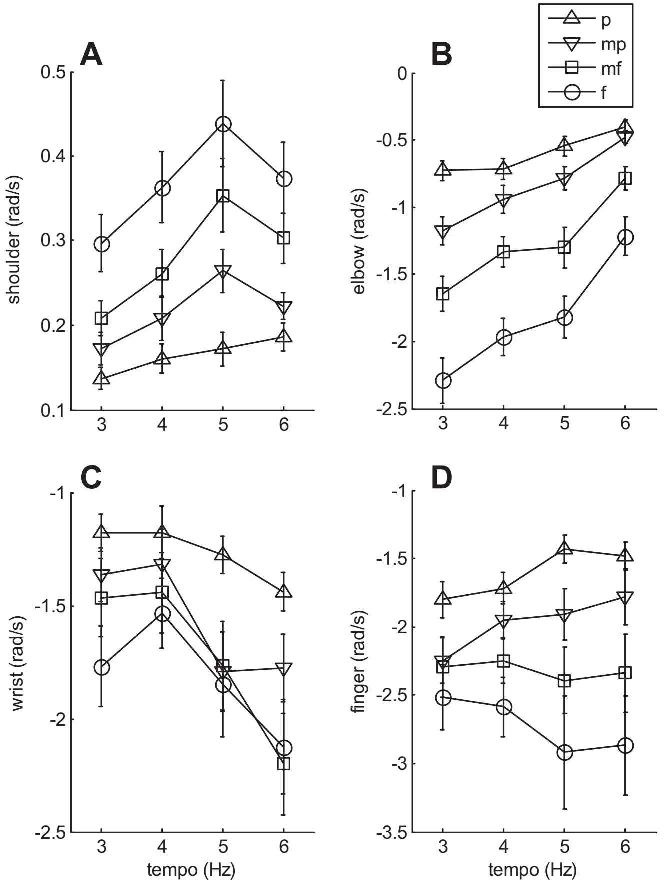

Fig. 2. The group means of the peak angular velocities for shoulder flexion (A), elbow extension (B), wrist flexion (C), and finger flexion (D) at four striking tempi and four loudness levels. The plots with triangle up, triangle down, square, and circle represent the loudness of *p*, *mp*, *mf*, and *f*, respectively. Error bars represent ±1 *SE*.

elbow and finger, respectively. Cluster 2 showed positive coefficients for the shoulder and wrist and a negative coefficient for the finger. Cluster 3 showed negative coefficients for the elbow and wrist joints.

Fig. 5 displays the average of the regression coefficients related to the interaction effect on kinematics and muscular activity across subjects in each of the three clusters. For the peak velocity (Fig. 5A), the coefficient for the shoulder was positive for clusters 2 and 3, and close to nil for cluster 1. The coefficient for the elbow was negative for all clusters and was particularly small for cluster 3. The coefficient for the wrist was fairly small, positive, and negative for clusters 1, 2, and 3, respectively. The coefficient for the finger was positive, negative, and fairly small for clusters 1, 2, and 3, respectively.

For the mean muscular activity (Fig. 5B), the coefficients for both the PD and AD showed large positive values for clusters 1 and 3 but not for cluster 2. For the triceps, the coefficient was positive for all clusters. For the biceps, the coefficient showed a large positive value for cluster 3 but was fairly small for clusters 1 and 2. For the FDS, the coefficients for clusters 1, 2, and 3 were positive, negative, and almost zero, respectively. For the EDC, only cluster 1 showed a clearly positive value.

For the CI (Fig. 5C), the coefficients for all muscles showed a large positive value in both clusters 1 and 3, whereas cluster 2 showed small negative coefficients for the shoulder and forearm and a positive coefficient for the upper-arm.

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Table 1
F values of two-way ANOVA with repeated measures for the peak angular velocity, mean muscular activity, and co-activation index (CI).

	Loudness	Tempo	Loudness × Tempo interaction
Peak angular velocity			
Shoulder	$F(3, 51) = 37.6^{**}$	$F(3, 51) = 7.3^{**}$	$F(9, 153) = 4.2^{**}$
Elbow	$F(3, 51) = 115.9^{**}$	$F(3, 51) = 43.3^{**}$	$F(9, 153) = 9.1^{**}$
Wrist	$F(3, 51) = 14.6^{**}$	$F(3, 51) = 9.0^{**}$	$F(9, 153) = 3.3^{**}$
Finger	$F(3, 51) = 20.7^{**}$	$F(3, 51) = 0.2$	$F(9, 153) = 3.8^{**}$
Mean muscular activity			
PD	$F(3, 51) = 20.6^{**}$	$F(3, 51) = 23.8^{**}$	$F(9, 153) = 5.8^{**}$
AD	$F(3, 51) = 5.0^{**}$	$F(3, 51) = 5.3^{**}$	$F(9, 153) = 3.6^{**}$
Triceps	$F(3, 51) = 17.8^{**}$	$F(3, 51) = 29.3^{**}$	$F(9, 153) = 8.8^{**}$
Biceps	$F(3, 51) = 9.3^{**}$	$F(3, 51) = 10.6^{*}$	$F(9, 153) = 3.8^{**}$
FDS	$F(3, 51) = 14.6^{**}$	$F(3, 51) = 7.8^{**}$	$F(9, 153) = 2.6^{**}$
EDC	$F(3, 51) = 36.4^{**}$	$F(3, 51) = 50.6^{**}$	$F(9, 153) = 6.9^{**}$
Co-activation index (CI)			
Shoulder	$F(3, 51) = 9.4^{**}$	$F(3, 51) = 15.7^{**}$	$F(9, 153) = 2.8^{**}$
Upper-arm	$F(3, 51) = 13.1^{**}$	$F(3, 51) = 16.2^{**}$	$F(9, 153) = 3.5^{**}$
Forearm	$F(3, 51) = 35.8^{**}$	$F(3, 51) = 27.0^{**}$	$F(9, 153) = 3.9^{**}$

* $p < .05$.
** $p < .01$.

4. Discussion

4.1. Interaction of loudness and tempo on joint kinematics and muscular activity

We found that the mean activity of the upper-extremity muscles showed greater increases with tempo when eliciting louder tones. Similarly, the peak velocity at the shoulder, wrist and finger joints exhibited greater increases with tempo when louder tones were produced. These findings indicate that the interaction of loudness and tempo on muscular activity is responsible for the production of large velocities at these joints. In addition, the co-activation index showed a greater tempo-related increase when eliciting louder tones. The increased muscular activity can therefore also be associated with increased joint stiffness. This had been expected from previous findings with respect to the so-called "Fitts' Law" (Fitts, 1954) and the relation between joint stiffness and movement accuracy (Gribble, Mullin, Cothros, & Mattar, 2003; Wong, Wilson, Malfait, & Gribble, 2009). For example, an increase in joint stiffness during the target-aiming task has been considered to increase the spatial accuracy of hand movements (Gribble et al., 2003). Also, the spatial accuracy decreases in proportion to movement acceleration (Fitts, 1954; Harris & Wolpert, 1998). The interaction effect on co-activation observed in our study may therefore play a role in ensuring movement accuracy against the demands of drastically increasing joint acceleration when striking both stronger and faster.

Conversely, for the elbow, the velocity exhibited a greater decrease with tempo at louder tones. This decrease in elbow velocity may be compensated for by increased velocity mostly at the distal joints. Counter-intuitively, the triceps activity showed a greater increase with tempo when eliciting louder tones. One explanation for this dissociation between elbow velocity and agonist muscular activity could be that the pianists failed to fully utilize gravity at faster tempi. We previously found that pianists utilize gravity to accelerate elbow extension during a discrete keystroke, and this effect becomes more pronounced when producing louder tones (Furuya et al., 2009). When striking faster in the present study, however, a clear burst at the triceps was observed, indicating the use of muscular force to accelerate the arm downswing. The transition from gravity-driven to muscular-driven keystrokes with increased tempo may therefore result in a greater increase in elbow muscular activity as loudness increases when striking faster.

Another explanation might be related to compensation of the inter-segmental dynamics. Due to the mechanical interaction between linked segments, a joint motion originates not only from the torque

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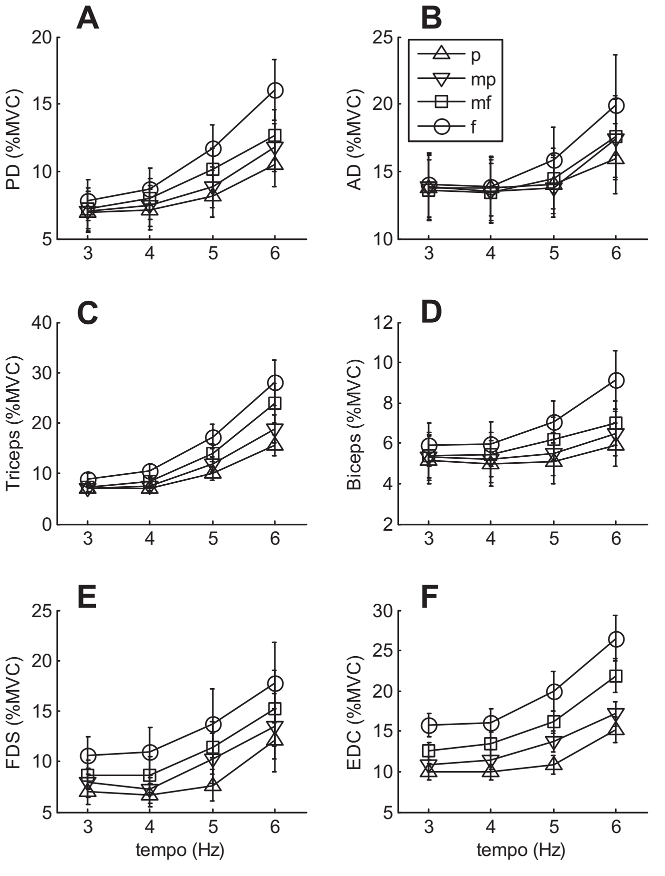

Fig. 3. The group means of mean muscular activity for PD (A), AD (B), triceps (C), biceps (D), FDS (E), and EDC (F) muscles at four striking tempi and four loudness levels. Error bars represent ±1 *SE*.

generated by its surrounding muscles but also from torque generated at the adjacent joints (Dounskaia, 2010; Hirashima & Ohtsuki, 2008). Muscular torque should therefore accurately compensate for these inter-segmental dynamics in order to generate a planned motion (Gribble & Ostry, 1999). Moreover, this compensatory muscular work increased at faster tempo in repetitive arm movements (Dounskaia, Swinnen, Walter, Spaepen, & Verschueren, 1998). Increased muscular activity and decreased joint velocity with tempo can therefore be attributed to an increased negative effect of the inter-segmental dynamics on elbow movements.

An early study by Ortmann (1929) investigated the effect of loudness and tempo on hand and arm movements during repetitive piano keystrokes. Based on the observation of different movement patterns across tempi and across loudness, he recommended that from the beginning, each passage should be practiced at that tempo or loudness at which it is finally to be played. Although this can be true, there is a concern related to playing fast or loud from the early stage of practice. Southard (1989) found that imposing a spatial accuracy demand while practicing a novel arm-swing movement resulted in the acquisition of a suboptimal movement pattern that failed to take advantage of the so-called "whip-like" motion (Furuya & Kinoshita, 2007; Hore, Debicki, & Watts, 2005). Since the spatial accuracy demand becomes higher with an increase in tempo and loudness, practicing piano keystrokes at fast tempo or large sound dynamics from the beginning of the practice may have the risk of preventing the acquisition of skilful movement coordination.

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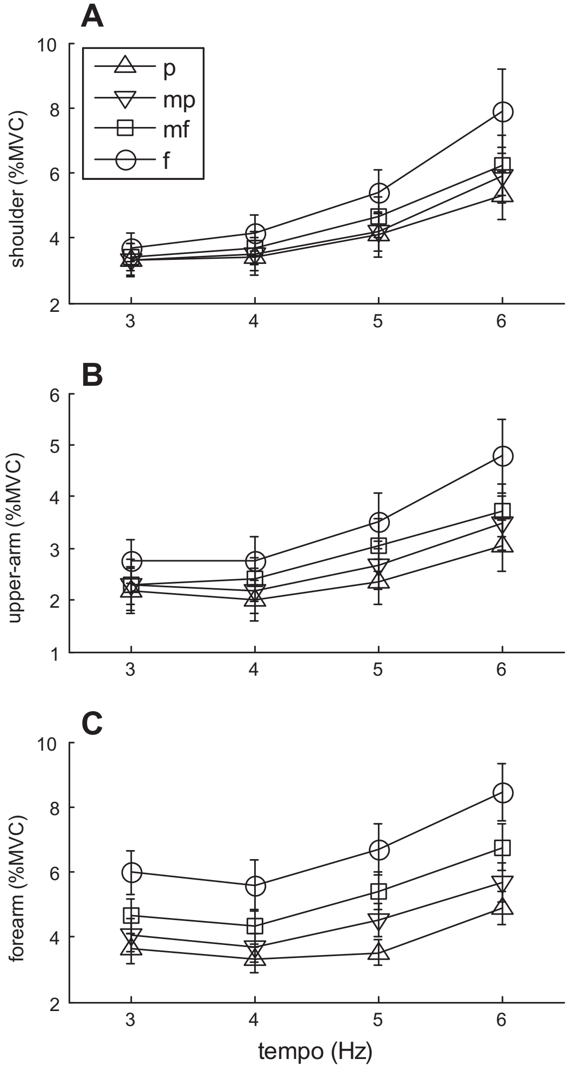

Fig. 4. The group means of the co-activation index (CI) for the shoulder (A), upper-arm (B), and forearm (C) muscles at four striking tempi and four loudness levels. Error bars represent ±1 *SE*.

4.2. Inter-pianist differences in the interaction effect

We identified three groups of pianists, each of which had distinct kinematic strategies to strike both stronger and faster. Cluster 1, which contained the largest number of pianists, compensated for the decreased elbow velocity predominantly by increasing the wrist and finger velocity. Consequently, the increases in both mean activity and co-activation of the forearm muscles in proportion to both loudness and tempo were larger than the other groups. This result may explain why the finger and wrist muscles have shown the largest incidences of playing-related musculoskeletal disorders (PRMD's) among pianists (Bragge et al., 2006; Furuya et al., 2006).

In contrast, pianists in cluster 2 exhibited relatively smaller coefficients regarding both the mean muscular activity and co-activation compared to the other clusters. In addition, they had negative

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Table 2
Partial regression coefficients to predict the loudnessxtempo interaction effect on individual joint velocity, and silhouette value for each subject. The coefficient corresponds to "*a*3" in the equation of multiple-regression analysis: $Y = a1 \cdot X1 + a2{\cdot}X2 + a3{\cdot}X1X2 + a4$. ($X1$: tempo, $X2$: loudness, Y: one of the kinematic and EMG variables at a particular joint/muscle.)

Cluster	Subject	Shoulder	Elbow	Wrist	Finger	Silhouette value
1	1	0.51	−1.33	0.56	0.86	0.29
	2	−0.07	**1.85**	−0.18	1.25	0.40
	4	*−0.16*	−1.05	0.64	1.26	0.59
	6	−0.12	−0.75	−0.31	1.54	0.61
	7	0.02	−1.09	−0.61	1.22	0.53
	8	0.10	−1.08	0.77	1.22	0.56
	10	0.07	−0.26	−0.09	**1.89**	0.57
	12	−0.01	−0.70	1.14	1.45	0.58
	14	0.09	−0.68	−0.62	1.47	0.58
	15	0.00	−0.05	−0.24	**1.89**	0.55
	16	−0.05	−0.98	0.94	1.21	0.57
	18	0.02	−0.69	0.66	1.66	**0.63**
2	9	0.28	0.13	**1.63**	−0.80	0.13
	13	**0.62**	−0.81	0.40	−1.48	0.24
	17	0.06	−0.24	0.78	*−1.61*	0.17
3	3	0.16	−1.93	−0.07	0.08	0.05
	5	0.32	−1.85	−0.37	0.21	*0.01*
	11	−0.10	*−2.43*	*−1.42*	−0.72	0.23

The positive and negative value of the coefficient indicated an increase and decrease in joint velocity in proportion to both loudness and tempo, respectively. The bold and italic numbers indicate a subject showing the largest and smallest coefficient/silhouette value, respectively.

coefficients for the shoulder and finger muscles, indicating decreases in mean activity and co-activation with concomitant increases in loudness and tempo. These findings suggest that pianists in this cluster increased both loudness and tempo in physiologically-efficient manner by alleviating muscular co-activation. This was surprising since we had expected an increase in co-activation for elevating joint stiffness against increased demands of spatial accuracy of movement when striking faster and stronger. Furthermore, the coefficient was smallest for the finger velocity and largest for the shoulder, elbow and wrist velocity, which suggested that they decreased specifically the finger velocity and instead increased the velocities of the more proximal joints. This also seems efficient because distal muscles are more fatigable than proximal ones. Since all pianists in this cluster had won prizes at international piano competitions, this may reflect a specialized strategy to more efficiently strike stronger and faster.

Pianists in cluster 3 showed the greatest decrease in elbow velocity with increases in both loudness and tempo across the clusters. In contrast, both the upper-arm co-activation and mean biceps activity had the largest coefficients. Hence, high joint stiffness may prevent these players from accelerating their elbow motion. Moreover, they showed a positive coefficient for the shoulder velocity and a small negative coefficient for the wrist and finger velocities, which indicates that the decrease in the elbow velocity when striking both stronger and faster was compensated for by increasing the shoulder velocity.

4.3. Clinical implications for PRMD's

We found three kinematic strategies to strike stronger and faster. Most pianists exhibited a decreased elbow velocity and increased finger velocity. The remaining pianists were characterized by either a large decrease in the finger velocity and its compensation by the surrounding joints or by a considerable decrease in the elbow velocity and increase in the shoulder velocity. In addition, the muscular load considerably differed depending upon the kinematic strategy. Importantly, all of these pianists could successfully increase both loudness and tempo irrespective of their strategies due to the redundancy of the motor system. The first clinical implication of our findings is that kinematic

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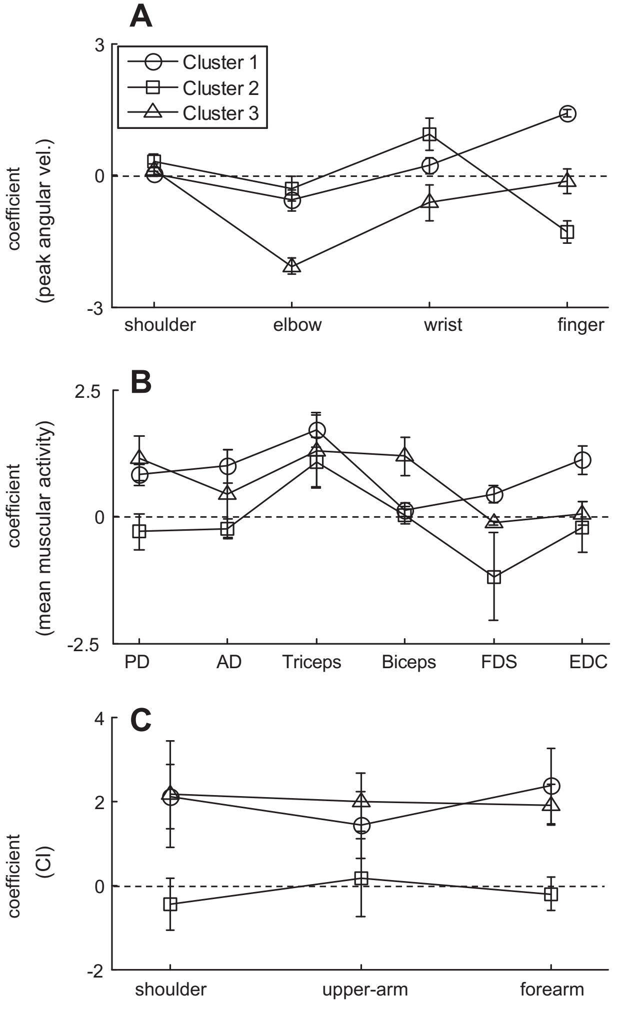

Fig. 5. A comparison of the group means of the regression coefficient with respect to the interaction effect of loudness and tempo on the peak angular velocity (A), mean muscular activity (B), and co-activation index (CI) (C) across clusters. The coefficient corresponds to "$a3$" in the equation of multiple-regression analysis: $Y = a1 \cdot X1 + a2 \cdot X2 + a3 \cdot X1 \cdot X2 + a4$ ($X1$: tempo, $X2$: loudness, Y: one of the kinematic and EMG variables at a particular joint/muscle). Plots with circle, square, and triangle indicate clusters 1, 2, and 3, respectively. Error bars represent ±1 *SE*.

information from individual pianists may be useful to determine muscles with the greatest potential risk of PRMD's. This would allow for both prevention of occurring PRMD's and accurate diagnosis of the cause of PRMD's. Second, the prevention of recurrent PRMD's may be enabled by acquiring a different keystroke strategy that has a reduced load on the muscle with a history of PRMD's. For example, previous studies reported that pianists' PRMD's occurred most frequently at the hand and forearm (Bruno et al., 2008; Furuya et al., 2006). In agreement with these, a majority of our subjects who were categorized in cluster 1 showed a considerable increase in the finger muscular load when striking stronger and faster. It is possible that pianists having a history of PRMD's at the finger muscles located in the hand and forearm can decrease the risk of its recurrence by newly acquiring the strategy used by pianists in cluster 2.

5. Conclusions

In summary, the present study successfully clustered eighteen pianists into three groups in terms of the interaction of loudness and tempo on movement kinematics during repetitive keystrokes. In addition, the muscular load considerably differed across groups, providing quantitative information that allows for predicting the muscles with a potential risk of repetitive strain injuries based on movement kinematics. The information is particularly important for preventing the injuries among active pianists who perform hours of practice each day (Jabusch, Alpers, Kopiez, Vauth, & Altenmüller, 2009). A parallel study that uses forward and inverse dynamics analyses is being carried out to identify dynamic causes that produce the individual differences in movements and muscular activities across pianists.

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