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Neuromuscular incoordination in musician's dystonia

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ABSTRACT

Introduction: The present study aims to define patterns of muscular activities specific to focal task-specific dystonia (FTSD), and classify them according to their association with the degradation of fine motor control or compensation for it.

Methods: While thirteen pianists with FTSD and ten expert pianists played several melodies on the piano, the activity of eight intrinsic and extrinsic finger muscles and the key-striking movements were recorded. To exclude the confounding effects of expertise, twelve amateur pianists also participated. The muscular activities were analyzed with a non-negative matrix factorization, an unsupervised classification technique, and multiple regression analysis.

Results: Six different patterns of muscular coordination were identified, each of which was responsible for the keystroke with each of the five digits and co-contraction between an antagonistic pair of finger muscles. A comparison between the healthy pianists and pianists with FTSD found no evidence of FTSD-related elevation of the co-contraction. A regression analysis between the muscular coordination and the key-striking movements further identified 23.4% and 20.8% of the FTSD-related changes in the muscular activity as associated with the movement degradation (i.e. delayed transition of the finger motion from flexion to extension) and compensation for it, respectively. The former was associated not only with hyper-activation of the flexor, but also with reduced-activation of the extensor.

Conclusions: The present study specified neuromuscular maladaptation relevant to the FTSD symptom, which suggests that muscular incoordination rather than muscular co-contraction characterizes pathological feature of FTSD in musicians.

1. Introduction

Aberrant muscular activities accompany various movement disorders. Focal task-specific dystonia (FTSD) is characterized by involuntary muscular spasms and overflows [1,2] primarily when performing trained motor tasks requiring the repetition of movements with high accuracy demand [3]. Studies using electromyography (EMG) reported that patients with FTSD typically display abnormal elevation of co-activation of an antagonistic pair of muscles [1,2,4,5]. Consistent with the observation, the pathophysiology of FTSD includes functional abnormalities of the sensorimotor systems subserving dexterous movement production. Studies using transcranial stimulation have reported abnormal excitability at the motor cortex in patients with FTSD [6–9]. For example, patients with FTSD at the hand showed an abnormal reduction of inhibitory control of the finger muscles irrelevant to task performance [10,11], which implies the incoordination of activities across multiple muscles. Aberrant coordination of activities across muscles has been also reported in other movement disorders, such as stroke [12] and spinal cord injury [13]. A behavioral study further identified the reduced independence of movements between fingers in patients with FTSD [14]. In contrast, a recent study found considerable similarities in the spatiotemporal patterns of muscular coordination between children with and without dystonia [15], which proposes the alternative possibility that FTSD has no effect on muscular coordination. It therefore remains unclear whether FTSD alters muscular coordination, and in what manner, if any, the altered coordination is related to the symptom. Indeed, dystonia patients often display abnormal muscular contraction compensating for the symptom, which complicates elucidating functional roles of dystonic muscular activities. It is clinically significant to classify abnormal muscular activation patterns due to FTSD according to whether they are associated with the degradation of fine motor control or compensation for it, which can

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optimize diagnosis and intervention specifically to a symptomatic muscle.

In the present study, a direct comparison of patterns of coordination across multiple finger muscles between healthy skilled and unskilled pianists and pianists with FTSD segregated patterns specifically associated with FTSD and expertise. The altered activities were further classified according to their covariation to the movement dexterity into the pattern associated with the performance degradation and the one compensating for it. Dissociating the effects of expertise and FTSD on muscular coordination can shed light on the neuroplastic mechanisms underlying motor dexterity, since muscular coordination is likely represented in the nervous system as a unit of neuromuscular control of skilled movements [16,17].

2. Methods

2.1. Participants

Thirty-five pianists participated in the study. The patient group consisted of thirteen pianists with FTSD (Supplementary Table 1). The healthy pianist group consisted of two subgroups with different levels of expertise; twelve amateur pianists without any experience of studying in music conservatories and ten expert pianists who underwent professional education in piano playing and won prizes at piano competitions. None in either subgroup had a history of neurological disorders. All patients underwent a thorough neurological examination by neurologists specializing dystonia and were diagnosed with a single finger (either index or middle) affected by FTSD. In accordance with the Declaration of Helsinki, the experimental procedures were explained to all participants. Informed consent was obtained from all participants prior to participation in the experiment, and the whole experiment protocol was approved by the ethics committee of Sophia University.

2.2. Experimental design

We asked the participants to play three short melodies three times with each hand on a digital piano. A sequence of notes in each melody used the same fingering with each of the hands. The first task (“scale”) is a two-octave C-major scale, striking fifteen adjacent keys successively in both rightward and leftward directions. The second task (“half octave”) is successive strikes of five adjacent keys bi-directionally with a closed hand posture. The third task (“arpeggio”) is to strike five non-adjacent separate keys bi-directionally, which requires keeping the hand opened. Participants played each task at specified tempo (80 bpm) (“paced tempo”) and as fast as possible (“fastest tempo”) at a designated loudness level (mezzo-forte; 80 MIDI velocity). Prior to each trial at the paced tempo condition, a melody to be played was auditorily provided by a digital piano at a target tempo and loudness. Following each trial, we assessed whether the loudness was within a range from 72 to 88 MIDI velocity (i.e. ± 10% of the target velocity) and whether participants made any pitch error, and if not, the trial was asked to be repeated.

2.3. Data acquisition

Using surface EMG, we recorded the activity of eight intrinsic and extrinsic finger muscles: abductor pollicis brevis (APB), the first, second, third, and fourth dorsal interossei (1DI, 2DI, 3DI, and 4DI), abductor digiti minimi (ADM), extensor digitorum communis (EDC), and flexor digitorum superficialis (FDS) of the both hands. The signals were acquired using a wireless EMG system with miniature active electrodes (Trigno mini, Delsys inc.) and an Analog-Digital board (NI-6129, National Instruments) at a sampling rate of 1 kHz. We also recorded MIDI data from the piano synchronized with EMG signal acquisition: the timing of the keypresses and key-releases and the velocity (loudness) and pitch of the keypresses.

2.4. Data analysis

Supplementary Fig. 1 summarizes the data analyses consisting of feature extraction, classification, and regression.

2.5. Preprocessing

Following the preprocessing of the EMG data (6th-order bandpass Butterworth filter with a cutoff of 10–450 Hz and a notch Butterworth filter with a cutoff of 48–52 Hz) to remove movement artifacts and power source noise, data was full-wave rectified, low-pass filtered (6th-order Butterworth filter with a cutoff of 20 Hz), and normalized according to the maximum value of each muscle's EMG signal obtained across all the experimental tasks. The EMG data were normalized to a fixed temporal duration of 4000 sampling points. At each sampling point of the 4000-point-long windows, a median value across the trials was computed to minimize contamination of occasional high-amplitude spikes arising from noise.

2.6. Assessment of muscular coordination patterns

The time-invariant muscular coordination patterns (feature vector) and their time-dependent activation coefficients (feature score) were extracted from the EMG signals of each hand using a non-negative matrix factorization (NMF) algorithm [18], which has the following mathematical form:

$$\mathbf{d}(t) = \sum_{i=1}^{N} \mathbf{w}_i c_i(t)$$

where $\mathbf{d}(t)$ is an 8×4000 matrix representing the EMG data of each trial, N is the number of muscular coordination patterns, $\mathbf{w}_i$ is an eight-dimensional feature vector representing each coordination pattern, and $c_i(t)$ is a feature score of the i-th coordination pattern. Each component of $\mathbf{w}_i$ represents the relative contribution of each muscle in the i-th coordination pattern. The extracted coordination patterns (feature vector) and their activation pattern varying over time (feature score) were normalized so that the Euclidean norm of each pattern could become 1. To identify the number of common and/or distinct muscular coordination patterns across tasks and groups, we classified muscular coordination patterns pooled across all datasets into a set of clusters using an unsupervised classification (k-means clustering) according to the similarity of coordination patterns in the eight-dimensional Euclidean space. We calculated the silhouette values [19] of each classification while changing the number of the clusters from two to eight in order to estimate the optimal number of clusters. We defined the optimal number of clusters as one that yields the largest mean silhouette value across all possible muscular coordination patterns.

2.7. Statistics

The present study addressed two specific research questions; whether the motor performance and muscular activities differ between the affected and unaffected hands in the FTSD patients, and whether they also differ between the unaffected hand of the patients, healthy experts, and healthy amateurs. If there is a difference between the affected and unaffected hands in the patients, then a lack of any differences between the unaffected hand of the patients and each of the healthy experts and amateurs indicates a difference between the affected hand of the patients and these healthy individuals. To test whether FTSD and expertise affected fine motor control during piano performance, a three-way mixed-design analysis of variance (ANOVA) with group (5 levels: amateurs, experts, intact hand of the patients, index-finger-affected patients [index FTSD], and middle-finger-affected patients [middle FTSD]), tempo (2 levels: paced and fastest), and task (3 levels: *scale*, *half octave*, and *arpeggio*) as independent variables was performed for the

within-trial average of the finger-key contact-duration. For each of the healthy individuals, we pooled the data of both hands. A three-way mixed-design ANOVA was also performed for the within-trial average of EMG signals of each muscle. Here we did not perform a four-way mixed-design ANOVA that consists of group, tempo, task, and hand (2 levels: right and left) instead of the three-way ANOVA. This was because the hand affected by FTSD differed across the patients (Supplementary Table 1), which made it unable to specify if a group and hand interaction effect indicates FTSD. We thus emphasize that the present statistics failed to test possible handedness effects, primarily due to that musicians' FTSD is a rare disorder that makes it difficult to recruit a sufficient number of patients whose affected hand is homogeneous. The present study therefore also performed a four-way ANOVA with factors of group (2 levels: healthy experts and amateurs), task, tempo, and hand (2 levels: right and left hands) only in the healthy pianists to test possible interaction effect of group and hand. To investigate any differences between the affected and unaffected hands of the patients, a three-way ANOVA was also performed only in the patients' data with factors of hand (3 levels: unaffected hand, affected hand of the index-finger-affected patients, affected hand of the middle-finger-affected patients), task, and tempo. Finally, to assess compensatory actions at the unaffected hand, a three-way ANOVA with factors of group (3 levels: unaffected hand of the patients, experts, amateurs), task, and tempo was performed. Post-hoc tests with corrections for multiple comparisons were also performed using a Benjamini-Hochberg method [20]. To assess whether novel patterns of muscular coordination emerge in a manner specific to task and group, a Pearson's chi squared-test was used to compare the occurrence rate of the classified muscular coordination patterns across tasks and across groups. Here in the healthy experts and amateurs, we pooled the data of both hands, whereas in the patients, we used the data of each of the unaffected hand of all patients, affected hand of the index-finger-affected patients, and affected hand of the middle-finger-affected patients.

To assess the relationship between muscular coordination and fine motor control, a stepwise multiple regression analysis was performed between the feature vectors of the individual muscles for the classified muscular coordination patterns and the finger-key contact-duration among all the participants and tasks at the fastest tempo. The contact-duration was used in the model because this is abnormally prolonged in pianists with FTSD, representing difficulty of quick transition of the finger motion from flexion to extension [7,14], whereas the keystroke velocity (i.e. loudness) was not sensitive enough to differentiate between the patients with FTSD and healthy pianists [21]. The regression model included all participants from both the healthy and dystonia groups, both on a theoretical basis of a heuristic model proposing a continuum from healthy to dystonic musicians, rather than two clearly-distinct groups [22] and on empirical findings supporting it [7]. Here, a Kolmogorov-Smirnov test confirmed normality of data of both the finger-key contact duration in all participants ($p = 0.062$) and residuals of the derived stepwise regression model ($p = 0.865$) in all participants.

3. Results

3.1. Motor performance and muscular activities

Fig. 1A represents group means of the averaged finger-key contact-duration. A three-way ANOVA yielded an interaction effect of group with both tempo ($F(4,65) = 5.76$, $p < 0.001$) and task ($F(8,130) = 3.00$, $p < 0.01$), but no three-way interaction ($F(8,130) = 1.91$, $p = 0.06$). Post-hoc tests identified longer contact-duration at the fastest tempo for the index-finger-affected and middle-finger-affected patients than the other three groups at all tasks, which indicated slower tempo played with the affected hand of the patients. The contact-duration at the fastest tempo was shorter for the experts than the amateurs while playing the *arpeggio*, which reflects expertise specifically when playing with keeping the hand opened. In addition, a four-way ANOVA only in the healthy pianists found that neither main effect ($F(1,20) = 0.004$, $p = 0.951$) nor interaction effects of hand with tempo, task, and group ($p > 0.05$) was significant. To further test specific effects of FTSD within the patients, a three-way ANOVA with factors of hand (unaffected hand, affected hand of the index-finger-affected patients, affected hand of the middle-finger-affected patients), tempo, and task was performed for the contact duration only of the patients. Significant interaction effects between the hand and tempo ($F(2,23) = 4.19$, $p = 0.028$) and between the hand and task ($F(4,46) = 3.37$, $p = 0.017$) and main effect of the hand ($F(2,23) = 5.17$, $p = 0.014$) were obtained. Post-hoc tests further confirmed significant differences at the fastest tempo between the intact hand and affected hand of the middle-finger-affected patients at all three tasks, and between the intact hand and affected hand of the index-finger-affected patients at the arpeggio task. By contrast, a group comparison using a three-way ANOVA with factors of group (healthy experts, healthy amateurs, and unaffected hand of the patients), tempo, and task failed to yield any significant effects of group ($p > 0.05$).

Fig. 1B represents group means of the averaged EMG values at each muscle. Three-way ANOVA yielded a significant group effect on EDC ($F(4,56) = 3.53$, $p = 0.012$) and group-task interaction effects on 3DI ($F(8,112) = 2.79$, $p = 0.008$) and EDC muscles ($F(8,112) = 7.17$, $p < 0.001$). The interaction effects indicate different effects of expertise and FTSD on muscular activities, depending on the tasks being performed. There was no uniform elevation/reduction of the activities at all muscles specifically in the patients, indicating FTSD-related changes in muscular coordination. Importantly, we did not observe larger activity at both EDC and FDS in the patients than the healthy groups at any tasks and tempi, which fails to support the FTSD-related elevation of co-contraction of an antagonistic finger extrinsic muscles. In addition, four-way ANOVAs only in the healthy pianists found no significant difference between the right and left hands at all of the six muscles except for the 1DI, in which the left-hand activity was significantly larger than the right hand only in the amateur pianists at the arpeggio task at the fastest tempo ($p = 0.001$). To further test specific effects of FTSD within the patients, a three-way ANOVA with factors of hand (unaffected hand, affected hand of the index-finger-affected patients, affected hand of the middle-finger-affected patients), tempo, and task was performed in the averaged EMG data of the patients. There were significant interaction effects between the hand and tempo at the FDI ($F(2,20) = 3.88$, $p = 0.038$), 3DI ($F(2,20) = 3.93$, $p = 0.036$), and 4DI ($F(2,20) = 6.54$, $p = 0.007$) as well as significant main effects of hand at the APB ($F(2,20) = 4.11$, $p = 0.032$), 3DI ($F(2,20) = 4.53$, $p = 0.024$), and 4DI ($F(2,20) = 7.70$, $p = 0.003$). Post-hoc tests further confirmed a significant difference between the unaffected hand and affected hand of either of both of the index-finger-affected and middle-finger-affected patients mostly at the fastest tempo at these muscles. Although a group comparison using a three-way ANOVA including the group (healthy experts, healthy amateurs, and unaffected hand of the patients), tempo, and task yielded significant interaction effects between group, tempo, and task at the APB ($F(4,84) = 3.77$, $p = 0.007$), 4DI ($F(4,84) = 2.56$, $p = 0.045$), and EDC ($F(4,84) = 3.29$, $p = 0.015$), post-hoc tests found that none of these muscles showed significant difference between the unaffected hand of the patients and each of the experts and amateurs ($p > 0.05$).

3.2. Muscular coordination patterns

To assess the covariation of activities across muscles and its alteration due to expertise and FTSD, we extracted patterns of muscular coordination from EMG signals using NMF. Two to four (in most cases, three) patterns accounted for more than 90% of the total variance. Fig. 2A represents the mean variance explained by the EMG data reconstructed by different number of coordination patterns from one to eight. We extracted three coordinations from each of the EMG datasets for between-group comparisons of the feature vectors of each

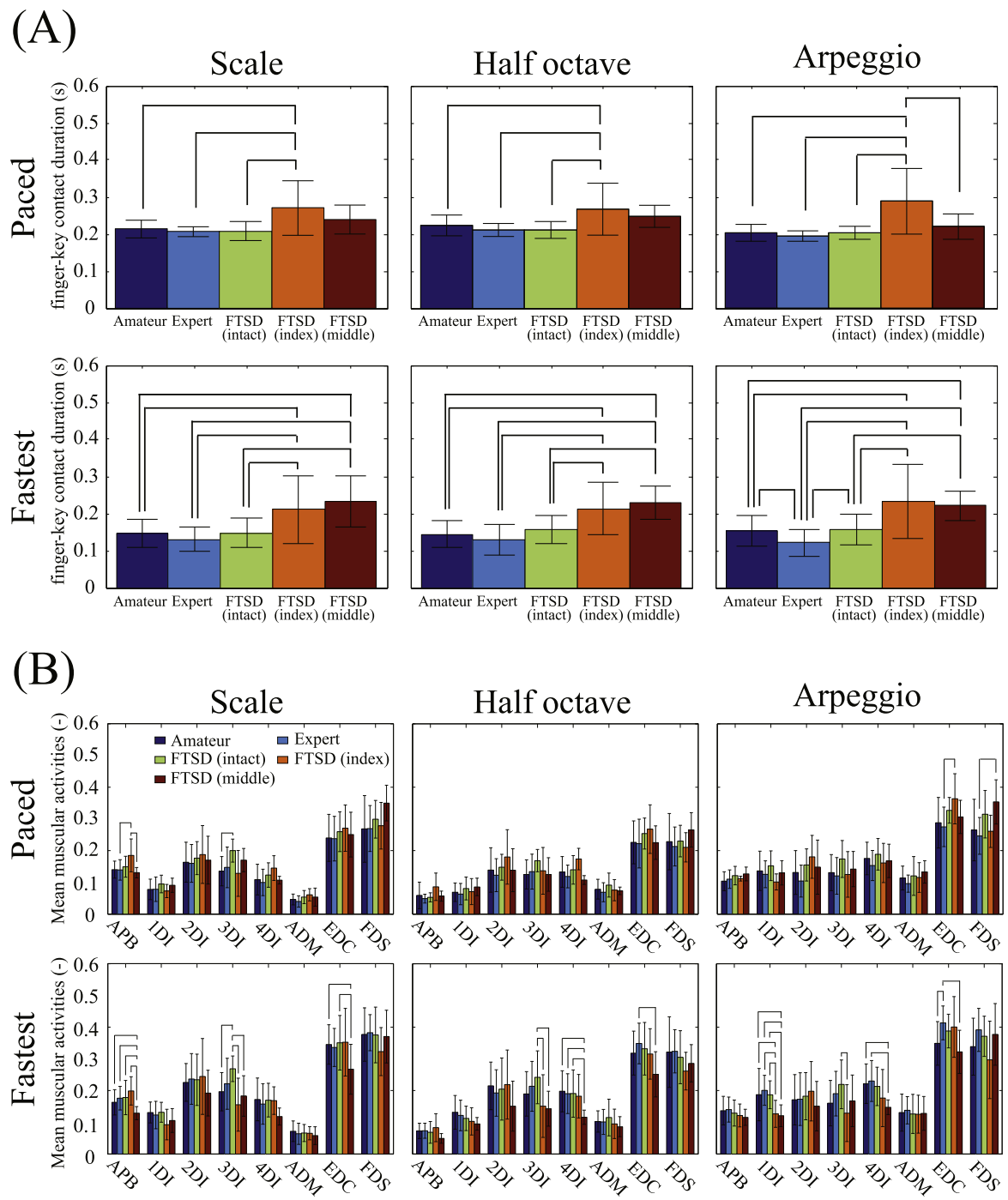
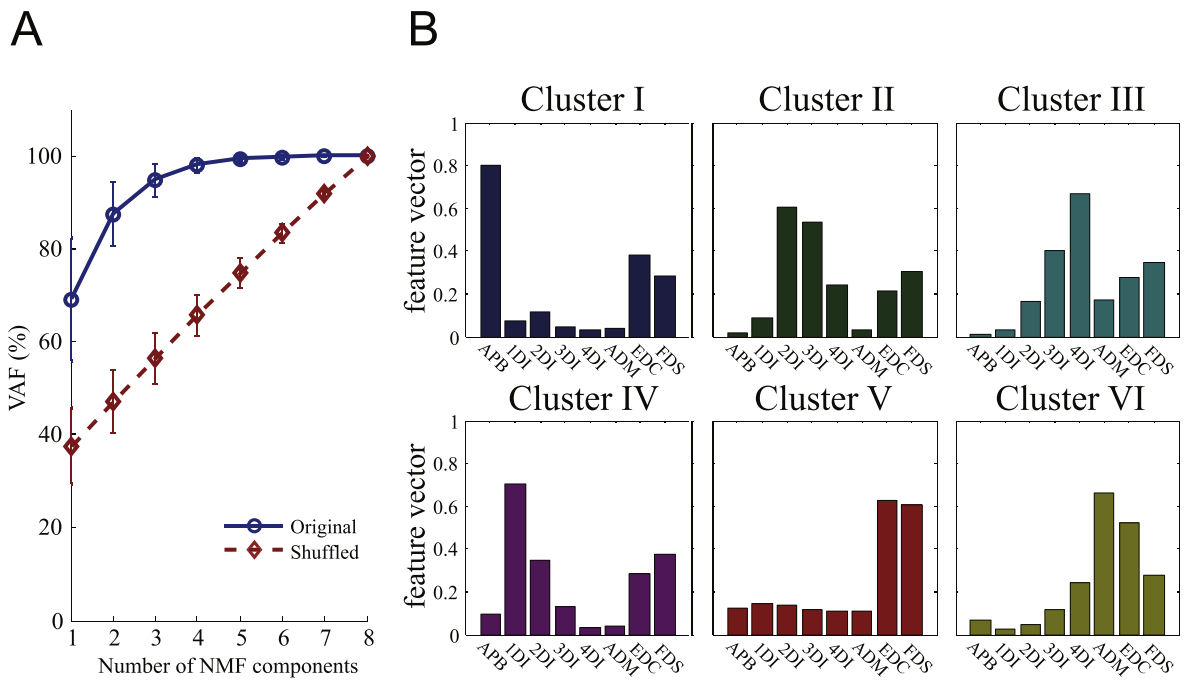


Fig. 1. Group means of the finger-key contact-duration (A) and the mean muscular activities (B) in each of the amateur pianists (dark blue), expert pianists (light blue), the intact (unaffected) hand of the FTSD patients (light green), the FTSD patients with an affected index finger (orange), and the FTSD patients with an affected middle finger (red) during each of the three tasks (i.e. Scale, Half octave, and Arpeggio) at the paced and fastest tempo. The horizontal bar between the box plots indicates a significant difference between two groups ($p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

coordination, which accounted for 92.3 ± 3.0% of the total variance of the original EMG signals. The shuffled result also indicates that the variance accounted for by chance [23] was smaller than the original datasets. K-means clustering classified the muscular coordination at all tasks and tempi for all groups according to their similarity. Fig. 2C shows the mean silhouette value of all coordination patterns extracted from all datasets when the muscular coordination was classified into two to eight clusters. The mean silhouette value was largest when classified into six, which was defined as the optimal number of clusters. Thus, muscular coordination of all the tasks, tempi, and groups was best classified into six patterns. Fig. 2B and D illustrate the centroids of the feature vectors and the time-varying feature scores derived from NMF for each cluster during the performance of each task at the paced tempo, averaged across all participants. Six different muscular activation patterns were characterized by the amount of activation of the individual muscles at each cluster (Fig. 2B), each of which was active primarily when striking with some specific fingering (Fig. 2D). Clusters I, II, III, IV, and VI represent the keypress with the thumb (e.g. *Scale*),



C

Number of clusters	2	3	4	5	6	7	8
Mean silhouette value	0.385	0.441	0.499	0.511	0.546	0.518	0.485

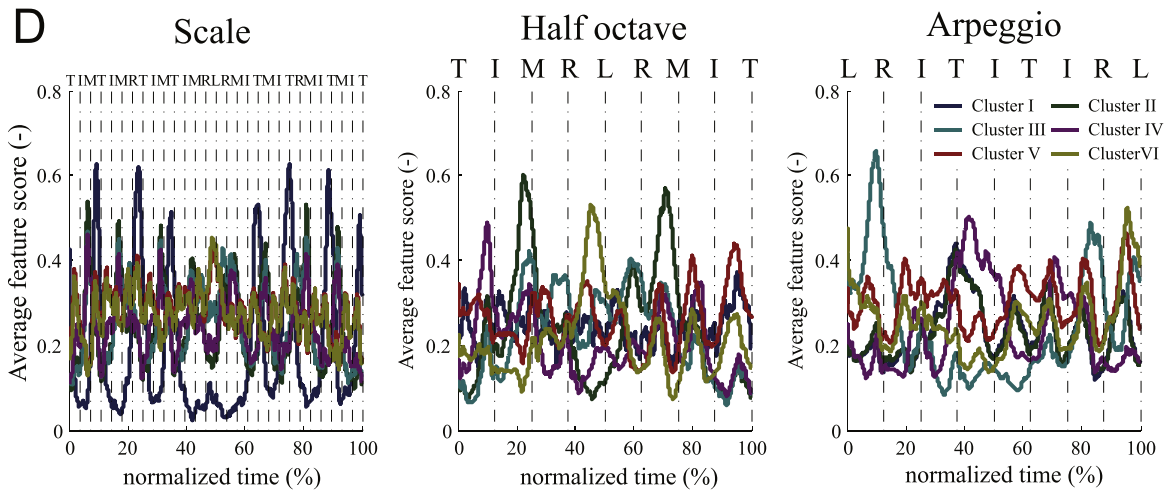


Fig. 2. (A) The mean variance accounted for (VAF) by the EMG data reconstructed from the different number of muscular coordination patterns from one to eight. The blue and red-dashed line indicates the VAF reconstructed by the original EMG data and randomly shuffled EMG data across muscles, respectively. The shuffled result indicates the VAF by chance (see details in Cheung et al., 2005), which was smaller than the original datasets. The centroids of the feature vectors (B) and the time-varying feature scores averaged across all participants during the performance of each of the three tasks at the paced tempo (D), both of which were derived from NMF for each of the six clusters (i.e. muscular coordination patterns) depicted in different colors. The feature vector describes which muscles were co-activated at each of the six muscular coordination patterns, whereas the feature score describes at which moment the individual muscular coordination pattern became active (i.e. T, I, M, R, and L indicates the moment of a keypress with the thumb, index, middle, ring, and little finger, respectively in Fig. 2D). The number of clusters was defined based on the mean silhouette value (Fig. 2C), in which the largest value was when the number was six. Based on the Figs. 2B and D, the clusters I, II, III, IV, and VI each represent the muscular coordination patterns responsible for the keypress with the thumb, middle, ring, index, and little finger, respectively, whereas the cluster V represents co-contraction between the finger extrinsic muscles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

middle-finger (e.g. *Half Octave*), ring-finger (e.g. *Arpeggio*), index-finger (e.g. *Arpeggio*), and little-finger (e.g. *Half Octave*). Although the feature score of Cluster V was not specifically related to a keypress with any particular finger, the feature vector of this cluster described co-contraction of the extrinsic finger muscles.

To investigate whether muscular coordination patterns were specific to task and/or group, chi-squared tests were performed. The frequency of the coordination patterns did not differ between the groups in all the tasks (*Scale*: $p = 0.912$, *Half octave*: $p = 0.850$, *Arpeggio*: $p = 0.105$). By contrast, the frequency of the coordination patterns

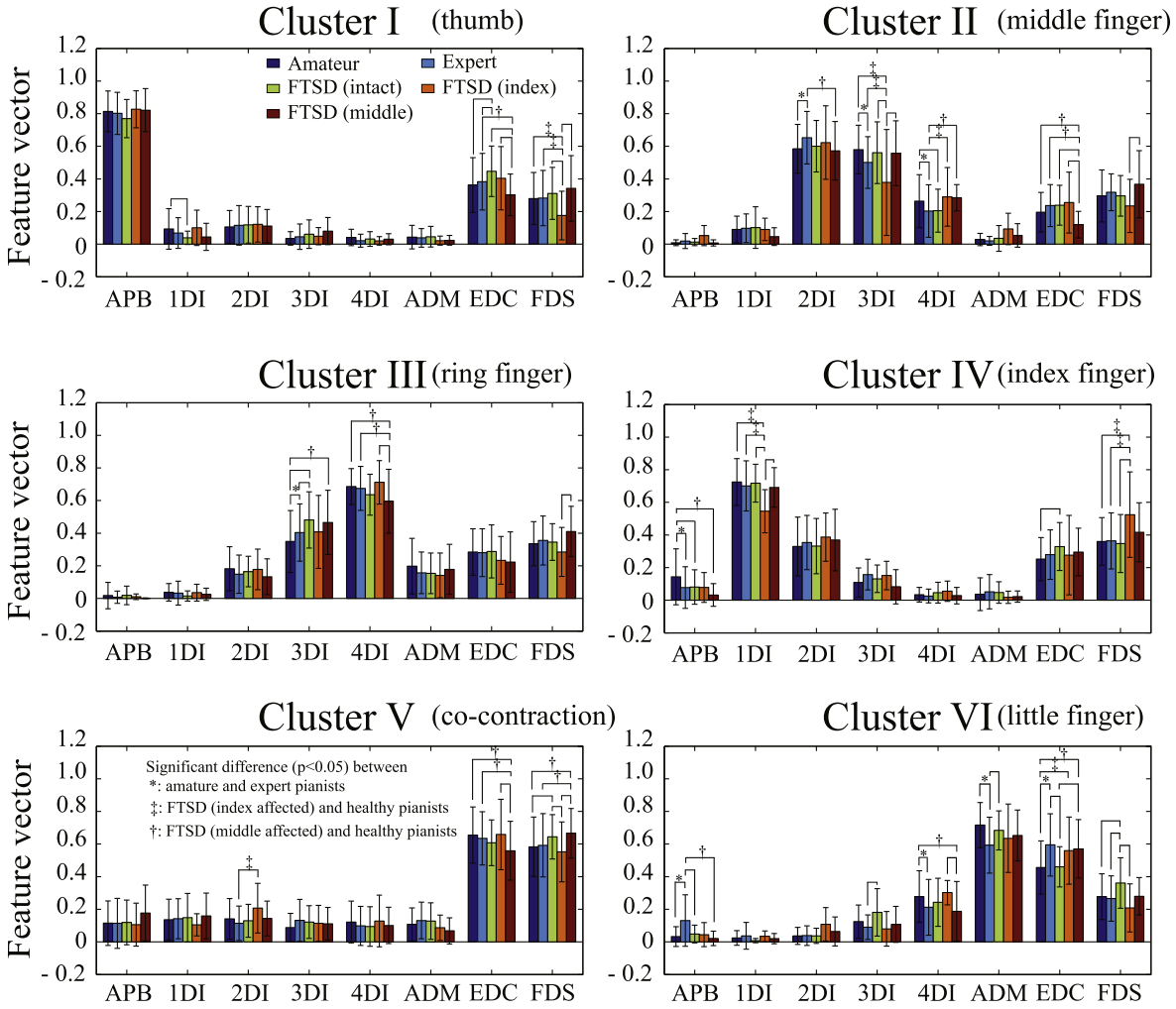


Fig. 3. Group means of the feature vectors at each of the six clusters in each of the amateur pianists (dark blue), expert pianists (light blue), the intact hand of the FTSD patients (green), the FTSD patients with an affected index finger (orange), and the FTSD patients with an affected middle finger (red). A significant group difference ($p < 0.05$) between the healthy amateurs and the expert pianists (*), between the FTSD patients with an affected index finger and healthy pianists (‡), and between the FTSD patients with an affected middle finger and healthy pianists (†). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

significantly differed between the tasks in all groups (Supplementary Table 2). These results indicate that the individual muscular coordination patterns reflect tasks, but neither expertise nor symptoms of FTSD. There was no coordination pattern specific to expertise and FTSD.

To characterize the alteration of muscular coordination patterns due to expertise or development of FTSD, the feature vector values were compared using t-tests with correction for multiple comparisons. Here, our datasets failed to be tested by ANOVA due to a highly unequal sample size between the clusters. Significant between-group differences were found for the feature vectors at each of the six coordination patterns (Fig. 3). At Clusters II, III, IV, and VI, the feature vectors of several muscles in the amateurs differed from the experts but not from the patients, indicating expertise-dependent alterations of muscular coordination (e.g. ADM at Cluster VI representing the little-finger keypress). By contrast, some had a difference not between the amateurs and experts but between the healthy individuals (amateur and/or expert) and patients, indicating FTSD-related alterations of the coordination (e.g. 1DI at Cluster I representing the thumb-keypress). At Cluster V representing co-contraction, the activity of the FDS and EDC was larger and smaller for the middle-finger-affected patients than the healthy group, respectively. This failed to support the abnormal elevation of the finger muscular co-contraction in the patients.

A multiple regression analysis was performed between the finger-key contact-duration and feature vectors of the muscular coordination patterns. Some of the feature vectors covaried with the contact-durations (Supplementary Fig. 2). Here, a positive coefficient means that increased activity of the corresponding muscle within a particular coordination pattern prolonged the finger-key contact-duration. The results showed a mixture of positive and negative coefficients, which indicates that the prolonged contact-duration was associated not only with increases but also with decreases of the muscular activities. To clarify roles of FTSD-related changes in the muscular activities in the prolonged contact-duration, Table 1 summaries the results of Fig. 3 and Supplementary Fig. 2 specifically at the muscles and clusters with significant group-wise differences. There were 3 patterns; FTSD-related changes in the muscular activity was associated with prolongation of the contact-duration, compensation for it, or neither of them. Table 1 describes that the same sign of both the group-wise difference and the regression coefficient (i.e. +/+ and −/−. See the caption of Table 1) mean an association of the muscular activity with motor deterioration, whereas a different sign (i.e. +/− and −/+. See the caption of Table 1) indicates its compensation. At the FDS of Cluster IV in the index-finger-affected patients, the feature vector was larger in the patients than the healthy (Fig. 3), and this activity covaried positively with the contact-duration (Supplementary Fig. 2). This indicates an

Table 1
An association of FTSD-related alteration of the activities in muscular co-ordination patterns with the prolongation of the finger-key contact-duration based on the results of the group-wise comparison and regression results.

Affected finger	Cluster	Muscle	Group-wise difference from healthy pianists	Regression coefficient	Compensation/ Deterioratioin
Index	I	FDS	–	N/A	N/A
	II	3DI	–	N/A	N/A
	II	4DI	+	–	Compensation
	IV	1DI	–	N/A	N/A
	IV	FDS	+	+	Deterioration
	V	2DI	+	+	Deterioration
	VI	EDC	+	N/A	N/A
Middle	I	EDC	–	N/A	N/A
	II	2DI	–	N/A	N/A
	II	4DI	+	–	Compensation
	II	EDC	–	–	Deterioration
	III	3DI	+	–	Compensation
	III	4DI	–	–	Deterioration
	IV	APB	–	N/A	N/A
	V	EDC	–	+	Compensation
	V	FDS	–	N/A	N/A
	VI	4DI	–	N/A	N/A
	VI	EDC	+	N/A	N/A

+/− in the group-wise difference indicates smaller/larger values of the feature vector in the patients compared with the healthy individuals.
+/− in the regression coefficient indicates positive/negative covariation between the muscular activity and finger-key contact-duration.

association of the increased FDS activity of the muscular coordination responsible for the index-finger keystroke (i.e. Cluster IV) with prolonged contact-duration. Another example was EDC of Cluster II (responsible for the middle-finger strike), in which the middle-finger-affected patients specifically showed a decreased activity (Fig. 3) and this activity covaried negatively with the contact-duration (Supplementary Fig. 2). The FTSD-related decrease of the EDC activity was therefore related to the prolonged contact-duration, again reflecting the symptom. These results associate the abnormal prolongation of the contact-duration not only with elevated flexor activity but also with drop of the extensor activity. By contrast, the EDC muscle at Cluster V representing the co-contraction exhibited a decreased activity specifically in the middle-finger-affected patients (Fig. 3), and the EDC activity covaried positively with the contact-duration (Supplementary Fig. 2). The FTSD-related decrease in the EDC activity was thus associated with shortening of the contact-duration, playing a role in compensating the motor degradation.

4. Discussion

We identified six distinct patterns of finger muscular coordination during piano playing. Intriguingly, there was no unique muscular coordination pattern specifically characterizing pianists with FTSD or skilled healthy players; rather, partial alteration within the pre-existing patterns by FTSD and expertise. Thus, FTSD and musical expertise do not yield specific muscular coordination, but alter the microstructure of the fundamental coordination. A regression analysis segregated the altered coordination due to FTSD according to whether it is associated with the degradation of motor dexterity or compensation for it. The former includes not only elevation but also reduction of muscular activities, which indicates that FTSD exacerbates coordinated activities across finger muscles.

Abnormal elevation of muscular co-contraction has been regarded as a phenomenon characterizing dystonia [1,2], which was however not observed in the present musicians with FTSD. A novelty of our study is to quantitatively classify muscular incoordination into symptomatic and compensatory activities. The analyses identified that the prolonged contact-duration, which reflects delayed initiation of the finger-lift following the key-depression [14], was associated with different muscular malfunctions in a manner depending on the finger affected by FTSD. The delayed finger-lift during the fastest performance was related to the increased FDS activity within the coordination responsible for the index-finger strike in the index-finger-affected patients, but to the decreased EDC activity within the coordination responsible for the middle-finger strike in the middle-finger-affected patients, respectively. By contrast, an elevated activity at a muscle adjacent to the affected index-finger compensated for the motor degradation, which indicates that hyper-activation of the muscle does not necessarily reflect the symptom. The detailed classifications not only clarified functional roles of abnormal muscular activities, but also potentially improves both diagnosis of FTSD and interventions for ameliorating the symptoms of FTSD by restoring the aberrant neuromuscular functions such as the injection of Botulinum toxin and EMG bio-feedback training [24]. A quantitative method for assessing FTSD, particularly musicians' dystonia, has not been established [25–27], which often causes misdiagnosis [28].

Several neural mechanisms possibly underlie the altered muscular coordination. First, musicians with FTSD displayed malfunction of motor cortex [6,7] that encodes coordinated muscular activities [17], which can underlie the FTSD-related muscular incoordination. Second, sensorimotor integration mechanisms are also abnormal in FTSD patients, such as reduced surround inhibition [10], which yields failure to move a finger with suppressing task-irrelevant finger muscles based on proprioceptive information encoding task characteristics. Third, somatotopy of the individual fingers are abnormally altered in FTSD patients (e.g. somatosensory cortex [29] and basal ganglia [30]), which can disrupt the fine-tuned sensorimotor integration in production of multiple finger movements. Finally, altered representation of movement sequence due to dystonia may affect the abnormal muscular incoordination during the finger movements [31].

Several limitations of the study should be mentioned. First, our study did not compare between the right and left hands of the patients statistically, since the hand affected by FTSD differed across the patients. The heterogeneity of our patient group is attributed to difficulty of recruiting a sufficient number of the FTSD pianists whose affected hand is homogeneous. Notably, four-way ANOVAs with group, task, tempo, and hand only in the healthy pianists identified overall no significant difference between the right and left hands. Second, the present study included the FTSD pianists with symptom at one single finger. It is therefore to be investigated whether the present classification is applicable for patients whose multiple fingers are affected by FTSD. Third, while all of the present patients reported and displayed the symptom at the present motor tasks (i.e. scale and arpeggio), there remain the other tasks that can trigger the symptom. Indeed, some patients reported the most pronounced symptom when playing octaves repetitively or playing the arpeggio with the black keys. Due to its task-specific nature, the motor abnormalities of the FTSD pianists should be investigated with a variety of musical tasks.

Conflicts of interest

We have no conflicts of interest to declare.

Financial disclosure

Both Dr. Oku and Dr. Furuya report no disclosures.

Authors' roles

OT and SF designed the study. OT collected and analyzed data. OT and SF wrote and revised the manuscript.

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Appendix A. Supplementary data

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