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Distinct digit kinematics by professional and amateur pianists

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Abstract

Many everyday tasks such as typing, grasping, and object manipulation require coordination of dynamic movement across multiple joints and digits. Playing a musical instrument is also one such task where the precise movement of multiple digits is transformed into specific sounds defined by the instrument. Through extensive practice musicians are able to produce precisely controlled movements to interact with the instrument and produce specific sequences of sounds. The present study aimed to determine what aspects of these dynamic movement patterns differ between pianists who have achieved professional status compared to amateur pianists that have also trained extensively. Common patterns of movement for each digit strike were observed for both professional and amateur pianists that were sequence specific, i.e. influenced by the digit performing the preceding strike. However, group differences were found in multi-digit movement patterns for sequences involving the ring or little finger. In some sequences, amateur subjects tended to work against the innate connectivity between digits while professionals allowed slight movement at non-striking digits (covariation) which was a more economical strategy. In other sequences professionals used more individuated finger movements for performance. Thus the present study provided evidence in favor of enhancement of both movement covariation and individuation across fingers in more skilled musicians, depending on fingering and movement sequence.

Keywords

Covariation; dynamic movement; fine motor control; independent finger movement; multi-digit coordination; long-term training

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1. Introduction

A wide variety of tasks require controlling dynamic movement of individual digits as in playing a musical instrument where the precision of pressing, striking or plucking by one or more digits determines the quality of the performance (Albrecht et al. 2014; Furuya et al. 2011; Goebel and Palmer 2013; Keller et al. 2010; Palmer et al. 2009). Dynamic patterns of covariation among joints within and across digits are observed during these movements in addition to other tasks such as typing, American Sign Language, and in grasping and manipulating objects (e.g. Jerde et al., 2003; Santello and Soechting, 1998; Soechting and Flanders, 1997; Weiss and Flanders, 2004). Patterns of coarticulation have also been observed where elements within a sequence are influenced by the preceding and subsequent elements (Engel et al., 1997; Jerde et al., 2003; Winges et al., 2013). The task itself influences the expected patterns of covariation and coarticulation. For example, the temporal constraints imposed by playing the piano often result in specific patterns of covariation across multiple-muscles and joints of the same limb, especially when larger movements are required to perform the next strike, such as a thumb-under maneuver (Engel et al., 1997; Furuya et al. 2011a). Without a specific rhythmic temporal constraint, movements similar to playing the piano such as typing tend to be executed in a more serial fashion where differences in spacing between strikes does not negatively impact task performance and may reflect biomechanical constraints (Soechting and Flanders 1992).

While the task itself may impose certain expected patterns of covariation, the actual patterns of movement can also be influenced by the ability to produce individuated finger movements. With training, changes in the performance of movement may reflect expertise. For example, in highly skilled pianists, very distinct patterns of inter-joint and multi-digit coordination were observed (Furuya et al., 2011a,b) and were maintained across different tempi (Furuya and Soechting, 2012). Comparative studies between the professional and amateur pianists have also demonstrated that professionals tend to have smaller amounts of spillover of force exerted by one finger to the adjacent fingers (Aoki et al., 2005; Parlitz et al., 1998; Slobounov et al., 2002). For example, repetitive piano keypresses with one finger while keeping the remaining digits immobilized yielded smaller magnitude and shorter duration of force exerted by the immobilized fingers in the professional pianists (Parlitz et al. 1998). In addition, hand kinematics of professional pianists was characterized by an equal amount of movement spillover across fingers (Furuya et al., 2011a), which differed from less individuated movements at the middle and ring fingers than the other digits in musically untrained individuals (Hager-Ross and Schieber 2000). Thus individuals with extensive piano training had superior independent control of finger movements against innate neural spillover and biomechanical linkages across digits (Lang and Schieber 2004; Schieber & Santello 2004; van Duinen et al 2009; Yu et al 2010; Zatsiorsky et al. 2000).

By contrast, neurophysiological studies using transcranial magnetic stimulation (TMS) provided evidence that professional pianists tend to have reduced suppression of motor neurons innervating muscles connected with the fingers adjacent to a moving finger (i.e. surround inhibition; Shin et al. 2012). Rosenkranz and colleagues (2005) also found reduced short intracortical inhibition in muscles controlling fingers adjacent to the finger controlled by the vibrated muscle in musicians, which could support lower surround inhibition among

digit muscles due to muscle spindle inputs. These findings indicate a greater readiness for producing coupled motion across fingers (multi-digit covariation) in the skilled players. The reduced surround inhibition is likely to result from repetitive training of the coupled motion between the fingers (Kang et al. 2013). Thus an alternative possibility is that for individuals who underwent extensive piano training, less pronounced individuated finger movements would be observed during performance.

The purpose of the present study was to characterize patterns of hand movements during musical performance by the professional and amateur pianists. Although increased independent control of the digits appears to be a one of the hallmarks of advanced training for dexterous movements, the influence of training on patterns of covariation among multiple digits is not known. Therefore, of particular interest were group differences in the amount of movement covariation, which could provide evidence for the two alternative influences of extensive musical training, i.e., does multi-digit control become more individuated or synergistic? Our general hypothesis was that highly trained pianists who had achieved “professional” status would exhibit patterns of multi-digit coordination reflecting an advanced level of control, such as economy of movement, compared to the amateur pianists.

2. Experimental Procedures

Ten healthy pianists (9 right handed, 4 male, 33 ± 10 yrs.) with no known neurological disorders or significant hand injuries participated in the study. Five of the subjects were professional pianists who had won prizes at international and/or national piano competitions, while the other subjects were amateur pianists with a range of training experiences (Table 1). The experimental protocol was approved by the University of Minnesota's Institutional Review Board and all subjects gave informed consent prior to the experiment.

Subjects played with the right hand, 14 different excerpts ranging from 9 to 24 sixteenth notes from 11 musical pieces which were: “Das Wohltemperierte Klavier, Vol. 1 No. 15 and Vol. 2 No. 1, 2, 10, 15” by Johann Sebastian Bach, “Étude Op. 10 No. 1, 4, 8 and Op. 25 No. 11, 12” by Frédéric Chopin, and “15 Études Op. 72 No. 6” by Moritz Moszkowski. The excerpts were selected for their use of the right hand and large number of fingering sequences without consecutive use of the same digit or of chords. Digit number was specified so that all subjects played with the same fingering. Subjects were instructed by demonstration to play at a loudness of 100 MIDI velocity in synchrony with a metronome which provided the tempo (inter-keystroke interval = 125 ms). Subjects were also instructed to play with legato touch (a key was not released until the subsequent key was depressed) and were allowed to practice to familiarize themselves with the piano and the musical excerpts so each excerpt could be played accurately and consistently across ten trials. Trials with mistakes were discarded (about 5-10% for professionals and 20-25% for amateurs). Discarding trials with mistakes limited our examination to accurate keystrokes which for amateur subjects may have resulted in playing at a slower than prescribed tempo.

Subjects played on a digital piano (Roland ep-5, 61 keys), connected to a Windows computer (SONY VAIO VGN-Z90PS) via a MIDI interface (Roland EDIROL UA-4FX).

The score and fingering was presented on a computer monitor in front of the piano. Posture of the right hand was defined by 15 joint angles measured by a right-handed glove with open fingertips with an angular resolution of the glove was $<0.5^\circ$ (Cyberglove, Virtual Technologies, Palo Alto, CA). The recorded joint angles from each of the four fingers were the metacarpalphalangeal (MCP) and proximal interphalangeal joints (PIP) as well as abduction (ABD) angles between the fingers. At the thumb, MCP, ABD and interphalangeal (IP) joint angles were measured as well as the angle of thumb rotation (ROT) about an axis passing through the trapezio-metacarpal joint of the thumb and index MCP joint. The glove was calibrated for each participant using a standard set of postures. Joint angle data were recorded at a temporal resolution of 12 ms (~ 83 Hz) for one second. A custom LabView script (National Instruments) was used to record joint rotations from the glove and MIDI data from the keyboard (1 ms resolution). Joint rotation data were differentiated to yield a set of joint angular velocities for each trial. The data were segmented into three-keypress sequences centered on each of the five target digits. For the central keypress by the thumb, index, middle, ring, and little finger, respectively, we analyzed $n = 25, 34, 29, 23$, and 17 three-keypress sequences yielded from the 10 excerpts for each subject. Relative joint movements were examined by segmenting the data ± 100 ms around the target digit strike. Peak joint velocity was defined as the maximum velocity in either the extension (positive) or flexion (negative) direction as determined by the sign of the average joint velocity ± 10 ms around the central strike.

Independent samples *t*-tests were used to determine whether MIDI performance variables differed between the professional and amateur subjects. To examine group and fingering differences on peak joint velocity, two-way mixed-design ANOVAs were used on peak joint velocity with independent variables GROUP (professional, amateur) and PreF (digit used for preceding strike) for each joint and striking digit. Tukey post hoc tests were used where appropriate to correct for multiple comparisons ($p < .05$).

To identify finger pairs that segregate between the professional and amateur subjects according to the movement covariation, we performed principal component (PC) analysis and cluster analysis. First, we computed correlation coefficients of movements between all possible pairs of fingers during the three-keypress sequences for each of all different fingerings (i.e. the central keypress with each of five digits and the preceding keypress with each of four fingers). This method provided a simple way to examine how pairs of digits move together. Note that phase relations between pairs of digits could influence the correlation coefficient such that digit pairs moving with phase relations near zero or 180 degrees (i.e., joint velocity changing in the same or opposite way, respectively) would result in correlation values near 1.0 and -1.0, respectively, while correlation values for intermediate phase relations (i.e., one joint leads or lags) would be smaller. The coefficient values of all subjects at each fingering was subject to the PC analysis, which yielded both PC values of all subjects and the corresponding coefficients that represent correlation coefficient values of all finger pairs for each PC. Using PC values of the first two PCs of all subjects, a cluster analysis using a support vector machine (SVM) was performed for each fingering. A binary classification by SVM identifies whether the datasets that represent movement covariation across fingers can be segregated according to whether the subject is

the professional or amateur players (Vapnik, 1995). To evaluate the performance of the cluster analysis, a leave-one-out cross validation (LOOCV) was carried out. In a LOOCV, each dataset is treated as the testing dataset only once, and serves as the training dataset N-1 times, where N is the total number of datasets (= 10 subjects), and therefore the parameters need to be tuned N times. This yields the number of misclassified testing dataset, which was divided by the total number of datasets and then subtracted from 1. This value was defined as the LOOCV score that represents whether the datasets can be classified by groups (chance level = 0.5).

3. Results

3.1 General performance

The ten pianists who participated in this study began training in childhood and continued to play as adults. The pianists were designated as professional (P) or amateur (A) based upon whether playing the piano was their primary career or was recreational, respectively (Table 1). Ages ranged from 19-54 years old and years of training ranged from 13-48, therefore this sample included a wide range of expertise and training over which to examine the hand kinematics of neurologically healthy pianists.

The MIDI signal from the piano contained performance information shown in Table 1 including keypress velocity (loudness), and timing of the keypress used to calculate contact duration for each keypress and the time between keypresses i.e., inter-keypress interval (IKI). While some amateur pianists had more training than some of the professionals, their performance was more closely linked to their group based on professional or amateur status. The IKI of 125 ms was instructed by having subjects play along with a metronome. The professionals played very accurately with mean IKIs from 122-126 ms with small variation. One amateur also played close to the instructed IKI while the other four amateurs tended to play more slowly with average IKIs from 140-155 ms and with larger variability. Likewise, amateur subjects tended to have longer contact durations and were more variable than professionals. Amateurs tended to play more softly than the demonstrated 100 MIDI velocity (loudness) with the exception of professional subject 3; while MIDI velocity for the other professionals averaged within 6% of the demonstrated MIDI velocity. ANOVA with Tukey post hoc revealed significant differences for GROUP (professional, amateur) as shown in Figure 1.

3.2 Kinematics

Patterns of joint velocity were examined across subjects and groups to determine whether differences between the two trained groups could be revealed. Mean patterns of MCP and PIP joint velocity are illustrated for one professional and one amateur pianist for index finger strikes preceded by the other four digits (Figure 2) and ring finger strikes preceded by the other four digits (Figure 3). Notice the similarity between subjects specifically in the MCP joints of the striking index (Figure 2) and ring (Figure 3) finger and the other non-striking digits. The striking finger MCP joint produces a flexion (negative) velocity that peaks around the time of the strike while the PIP joint velocity is often extension (positive). The velocity profiles of the non-striking digits appear to change depending on what digit

performed the preceding strike. The peak velocities during these single digit strikes were examined to determine whether movement at individual joints differed with respect to the digit performing the preceding keystroke and/or between professional and amateur pianists. Thus for MCP and PIP joints at each finger and thumb MCP, IP, and ROT, a separate two-way ANOVA on peak velocity for GROUP (professional, amateur) and PreF (digit used for preceding strike) with Tukey post-hoc was used. The results of ANOVAs for each joint during a specific digit strike with significant main effects and/or interactions ($p < .05$) are reported below.

For the most part the two groups were very similar on average. There were no significant main effects of GROUP on peak velocity for the thumb joints (MCP: all $F = 1.509$, all $p = .228$; IP: all $F = 2.212$, all $p = .147$; ROT: all $F = 1.756$, all $p = .195$), although GROUP differences were found at some finger joints. Figure 4 shows the cases where significant main effects for GROUP on peak velocity were revealed for the middle MCP during middle ($F_{1, 32} = 5.583$, $p = .024$) and ring ($F_{1, 32} = 7.773$, $p = .009$) finger strikes, little PIP during ring finger strikes ($F_{1, 32} = 7.855$, $p = .009$), and little MCP ($F_{1, 32} = 6.878$, $p = .013$) and ring PIP ($F_{1, 32} = 7.301$, $p = .011$) during little finger strikes. While peak velocity for both middle and little finger key strikes, differed at their respective MCP joints, amateur pianists used greater flexion velocities than professionals at the middle finger while the opposite pattern occurred at the little finger with a larger difference between groups. Similar to the little MCP, during little finger strikes the flexion velocity at the ring PIP was larger for the professional pianists. During ring finger strikes, at both middle MCP and little PIP the amateur pianists had extension velocities while professionals had smaller extension velocities. These results indicate that GROUP differences could occur in the joints of the striking digit and non-striking digits. In the case of ring and little finger strikes where GROUP differences occurred at more than one joint, the relative pattern between professional and amateur groups was similar across joints.

We also examined whether peak velocities of the MCP and PIP finger joints and thumb MCP, IP, and ROT were influenced by the preceding strike (PreF; Figure 5). Significant main effects of PreF on peak velocity were found in all *non-striking* MCP joints (all $F_{3, 32} = 3.050$, all $p = .043$) that tended to reflect the need for a larger extension velocity at the digit that performed the preceding strike. There were no significant main effects of PreF on peak velocity of the *striking* finger MCPs (all $F_{3, 32} = 1.556$, all $p = .21$) reflecting the consistency with which finger strikes were performed regardless of the preceding digit. However, there was a significant main effect of PreF on thumb MCP peak joint velocity during thumb strikes ($F_{3, 32} = 22.826$, $p < .001$); when the index or middle finger preceded the thumb strike, the thumb MCP produced small flexion velocities, whereas preceding strikes by the ring or little finger resulted in larger extension velocities at the thumb MCP. Significant main effects of PreF on thumb ROT peak joint velocity were found during all digit strikes (all $F = 8.843$, all $p < .001$). During thumb strikes preceded by the index or middle finger, a large internal rotation (negative ROT) was produced while an external rotation (positive ROT) occurred when the ring or little finger preceded the thumb strike. During other finger strikes, the significant effect of PreF reflected large external rotations that occurred when the thumb preceded the striking finger compared to the other digits. There were no significant

main effects of PreF on peak velocity for the thumb IP joint regardless of the striking finger (all $F_{3,32} > 1.831$, all $p < .161$). Main effects of PreF on peak joint velocity for the *finger* PIP joints followed a similar pattern to the MCP joints. Main effects of PreF on peak joint velocity for the PIP joints of the *striking* finger were not significant for the index, middle and little fingers (all $F_{3,32} < 2.00$, all $p > .134$). A significant main effect of PreF in the ring PIP ($F_{3,32} = 4.633$, $p = .008$) during ring strikes reflected the difference between ring strikes preceded by the index finger (-39.572 ± 24.784 deg/s) and little finger (84.676 ± 24.784 deg/s). Significant main effects in the *non-striking* digits reflected the tendency to produce larger flexion velocities at the joint responsible for the preceding strike. This trend occurred during all other finger strikes for the ring and middle finger (all $F_{3,32} > 3.911$, all $p < .017$), the index finger during thumb, middle, and little finger strikes (all $F_{3,32} > 3.124$, all $p < .039$), and the little finger during thumb and middle finger strikes.

A significant interaction of GROUP and PreF on peak velocity was only found at the thumb MCP joint during middle finger strikes ($F_{3,32} = 3.168$, $p = .028$; Figure 6). When the thumb preceded the middle finger strike, professionals produced small extension velocities at the thumb MCP while larger flexion velocities were produced by amateurs and by both groups when the index performed the preceding strike. Both groups produced flexion velocities when the ring or little finger performed the preceding strike.

3.3 PC and cluster analysis

To determine whether groups could be differentiated based on how pairs of fingers move relative to one another, correlations between pairs of fingers were used to define common patterns to be discriminated. The analysis was restricted to movement at the MCP and PIP joints of each finger since the previous analyses demonstrated that this is where the main differences between groups was likely to occur. For MCP and PIP joints separately, each digit performing the central keystroke, four separate PC analyses were used to examine patterns of covariation when the four other digits preceded the central stroke, i.e. separate PC analyses for the thumb central keystroke when preceded by the index, middle, ring, or little finger. For all subjects the first two PCs accounted for a *minimum* of 84% and 70% of the variance at the MCP and PIP joint, respectively. A cluster analysis using SVM was performed on the weightings of PCs 1-2 in order to determine if the covariation among pairs of digits could discriminate the professional from amateur pianists. Figure 7 shows two cases with relatively strong discrimination among the groups. For middle finger keystrokes preceded by the thumb, the first two PCs represent relations for all finger pairs with the exception of middle-ring. The first PC shows a pattern where the remaining finger pairs covary in the same way while PC2 represents opposing relations when the middle and ring finger are paired with the index (IM, IR) or the little finger (ML, RL). A second result is shown in Figure 7 for ring finger keystrokes that were preceded by the thumb. The first PC represents a difference in the covariation of the MCP joints for them index-middle (IM) finger pairing from the finger pairs. PC2 appears to represent a pattern where MCP joints of fingers paired to the index finger have a stronger relation than the other finger pairs. A clear group separation according to the sign of PC2 indicates synergistic movement covariation between the index and the remaining fingers, and individuated movements between the middle, ring and little fingers for the professionals rather than the amateurs. The results of

the cluster analysis are shown in Table 2. There were six out of forty cases in which the groups could be discriminated at a rate of 70%; four based on MCP and two for PIP joints. Table 3 shows the classification of individual subjects for each of these six cases. Subjects 6 and 10, both amateur pianists, were never misclassified, while most of the other subjects were misclassified for one or two of the cases. However, professional subject #5 was misclassified in four of the six cases.

Classifications involving additional higher PCs did not improve classification with the exception of four cases. In two cases there were modest improvements (middle strike with the index preceding strike at the MCP joint = +30%, ring strike with the thumb preceding strike at the PIP joint = +30%), while in the other two cases the classification rates were near zero until the third PC was included increasing the rate up to 70% and 60%. The first case in which a large improvement occurred was when the little finger preceded thumb strikes, the third PC reflected a pattern where the MCP joints of the index and middle fingers covaried with the little finger more for professionals. In the second case where index finger strikes were preceded by the little finger, PC3 represented strong covariation of the PIP joints for the middle-ring pairing for amateurs while the opposite was observed for professionals. Therefore, the main factor in classifications by group in this case was reflected in the tendency for professionals to move the middle and ring PIP joints more independently during the index finger strike.

4. Discussion

The pianists who participated in this study had trained for many years although only half had achieved the status of professional. The aims of this study were to examine dynamic movement patterns during piano playing and determine if fine elements of control could be identified that separated the groups based on their professional or amateur status. As expected, group differences in performance variables revealed that professionals were better able to keep the prescribed tempo and play at the instructed loudness (MIDI velocity) with less variability than amateur pianists. There were also notable differences in their digit movements during specific sequences of keypresses.

During each keypress, typical motion at the striking finger was characterized by MCP flexion and PIP extension. The extension of the PIP results in a stiffened finger through which force is transmitted to the key. For rapid movements, the coordination of MCP flexion and IP extension in the fingers is the direct result of contractions of the lumbrical and interosseus muscles. The opposite pattern (MCP extension/IP flexion) occurs through contractions of the extrinsic extensors and flexors for rapid movements, although for relatively slower movements passive mechanics can also contribute, i.e. extension at the MCP joint pulls on the flexor tendons that insert on the middle and distal phalanx of the finger resulting in flexion at the IP joints (finger curling). The thumb lacks muscles that can directly perform coincident MCP flexion/IP extension like the lumbrical and interosseus muscles of the fingers. Thus the thumb must rely on the coordinated activation of the extensor pollicis longus (the only extensor of the thumb IP joint) and flexor pollicis brevis to produce coincident MCP flexion and IP extension. At the adjacent fingers either this pattern of MCP flexion/PIP extension was maintained with flexion/extension amplitudes close to

zero at the time of the strike or the opposite pattern occurred, i.e. MCP extension and PIP flexion. Both anatomical and neurophysiological coupling can result in an adjacent digit producing an unwanted flexion movement during the adjacent finger strike (Lang and Schieber, 2004; Schieber and Santello, 2004; Winges and Santello, 2008). If independent movement at a specific digit is limited, it might be necessary to actively move the adjacent fingers in the opposite direction. Superior independent control of digits has been observed for highly trained pianists (Aoki et al., 2005; Furuya et al., 2011a), thus we expected this to be a point where movement patterns for professionals would differ from amateurs.

During most keypresses the velocity profile patterns in adjacent digits occurred in both groups reflecting relatively simple strategies to overcome limitations in independent finger movement. However, during ring and little finger strikes, there were clear breaks in the pattern that were features of distinction between the professional and amateur pianists. The first case occurred during little finger strikes where no difference occurred at the ring MCP joint but professionals produced significantly larger flexion velocities at the ring PIP while amateurs restricted this movement (Figure 4). Thus, amateurs tended to actively restrict or work against the natural ring PIP flexion that typically accompanies MCP extension while the professionals' strategy was more relaxed. This type of restriction by amateur subjects also occurred during ring finger strikes where professional pianists allowed a small flexion velocity ($< 20\%$ of ring MCP) in the adjacent middle MCP joint while the opposite occurred for amateurs (Figure 4). However, there was also a significant main effect of PreF for the ring finger strikes where large extension velocities were produced at the middle MCP joint when the middle finger preceded the ring finger strike and smaller flexion velocities were produced when the thumb preceded the ring finger strike (Figure 5). Although there was not a significant interaction of GROUP*PreF, the joint velocity data plotted in Figure 3 may provide some further interpretation of how the groups differed; professional subject #1 produced flexion velocities while amateur subject #10 restricted velocities to be closer to zero for strikes preceded by the thumb, index, and little fingers. In this case the amateur pianist was working more strongly against the coupling between the middle and ring fingers by restricting the middle MCP flexion except when the ring finger strike was preceded by the middle finger. Thus it seems likely that when a middle strike preceded the ring strike, both groups produced large extension velocities at the middle MCP to move it out of the way; the group difference then reflects the difference at the middle MCP when the thumb, index, and little fingers preceded the ring finger strike. Additionally, amateur subjects produced extension velocities at the little finger PIP joint while professionals produced small flexion velocities during ring finger strikes (Figure 4), in the absence of group differences at the little finger MCP joint. Therefore, amateur subjects resisted MCP-PIP coupling by exerting velocities opposite of the direction expected in order to straighten and extend the little finger during ring finger strikes. These results indicate that during ring and little finger strikes the professionals allowed more synergistic movement within and between adjacent fingers which may take advantage of the innate anatomical and neurophysiological coupling between digits (Lang and Schieber, 2004; Winges and Santello, 2008).

PC and cluster analyses of the movement coupling across fingers at individual sequences further demonstrated fingering-specific group differences in the movement kinematics (Table 2). In most cases, PC2 was responsible for segregating the movement pattern

between the professionals and amateurs (e.g. Fig. 4). For instance, during playing sequences where the thumb preceded the middle strike (Fig. 4A), PC2 represented positive coupling between the index and each of the middle and ring fingers, and negative coupling between the little and each of the middle and ring fingers. Positive coefficient values of PC2 for the professionals therefore indicate movement covariation between the index and the adjacent fingers and movement individuation between the little and the adjacent fingers, and vice versa for the amateurs who displayed negative coefficients. The result of movement covariation corroborates with the reduced surround inhibition between the index and little finger muscles in musicians (Shin et al., 2012). Also, our finding of the movement individuation is in agreement with superior independent control particularly at potentially less-independent finger pairs such as the ring finger (Aoki et al., 2005; Furuya et al., 2011a). This can be attributed to a less pronounced difference in the cortical activity associated with the index and ring fingers for musicians compared with non-musicians (Slobounov et al., 2002), anatomical changes that can lower biomechanical constraint on individual fingers in musicians (Smahel and Klimová 2004), or motor cortical reorganization due to musical training (Gentner et al. 2010). The skilled pianists also reduced coactivation of the finger flexor and extensor muscles (Winges et al. 2013), which can lower muscular stiffness and thereby decrease spillover of force exerted by one muscle into the adjacent muscles. This is because when one finger moves, lower stiffness at multi-tendon muscle results in production of smaller elastic force at its adjacent fingers, which eventually weakens the biomechanical constraint across fingers (Lang and Schieber 2004). Overall, the present study provided evidence in favor of enhancement of both movement covariation and individuation across fingers in more skilled musicians, depending on fingering and movement sequence. The professional pianists are likely to utilize a wider repertoire of multi-digit movement coordination than the amateurs, which may underlie finer motor control.

In only two cases, we found that higher PCs played a role in separating the groups in terms of movement patterns. In the first case, the third PC reflected stronger covariation among MCP joints of index-little and middle-little finger pairs for professionals when a thumb strike was preceded by the little finger. When the little finger strike preceded thumb strikes, the third PC represented movement covariation of the MCP joints of the index and middle fingers with the little finger, which was higher (stronger) for the professionals. By contrast, in the second case when the index preceded little finger strikes, the third PC reflected strong covariation of the PIP joints for the middle-ring finger pair for the amateurs such that these joints tended to move together with similar direction and velocity but for professionals these joints moved more independently of one another. Thus in these cases higher order PCs were essential in discriminating between the groups.

Long term musical training has widespread influences on brain function and structure that are specific to the innate requirements of the instrument (for review see Herholz and Zatorre, 2012). As with any movement that is highly repetitive there is the risk of overuse injuries. For musicians, the cortical changes that accompany the long term practice of their skill can introduce the potential risk of developing focal hand dystonia (Rietveld and Leijnse, 2013). This neurological disorder that is linked to overtraining yields loss of independent control of movements across fingers, which impairs fine motor control (Furuya and Altenmüller, 2013). The underlying neurophysiological mechanism can include loss of surround

inhibition (Rosenkranz et al., 2009) and enlargement of somatosensory representation of individual digits (Elbert et al., 1998). Indeed, repetitive training of the coupled motion between the fingers reduced surround inhibition (Kang et al., 2013), possibly which triggers deterioration of independent control of finger movements and eventually focal dystonia. In our study, the enhanced movement covariation at some finger pairs was a defining feature of movement for the highly-trained pianists. Thus for specific sequences the increase in covariation or lack of independent movement among pairs of fingers appeared to coincide with professional status. Although all of our subjects had undergone years of training, the specific differences in movement may represent differential cortical changes for more advanced multi-digit control. It is interesting and unfortunate that for a select few these enhancements may be related to their potential risks of developing focal hand dystonia.

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Highlights

- Skilled musicians exhibit enhanced covariation and individuation specific to movement sequence
- Professional and amateur pianists differ in movement pattern for ring and little finger sequences
- Amateur pianists appeared to work against the innate connectivity between digits

Figure 1. MIDI variables

Mean (+SE) and SD (+SE) for interkeystroke interval (IKI), MIDI velocity, and contact duration (CD) are plotted for Professional (Prof.) and Amateur (Am) groups. Significant differences between groups are indicated by *** $p < 0.001$.

Figure 2. Mean joint velocity profiles of a professional and amateur pianist during INDEX finger strikes

The average angular velocity is plotted for the MCP and PIP joints of each digit during index finger strikes preceded by each of the other four digits (individual lines) for one professional and one amateur subject. Joint velocity profiles are shown for ± 100 ms around the center strike denoted by a vertical dashed line.

Figure 3. Mean joint velocity profiles of a professional and amateur pianist during RING finger strikes

The average angular velocity is plotted for the MCP and PIP joints of each digit during ring finger strikes preceded by each of the other four digits (individual lines) for one professional and one amateur subject. Joint velocity profiles are shown for ± 100 ms around the center strike denoted by a vertical dashed line.

Figure 4. Significant main effects of GROUP on peak joint velocity

The mean ($\pm$ SE) peak velocity is plotted only for the individual joints during the designated finger strikes where there was a significant main effect of GROUP on peak velocity as revealed by two-way ANOVAs with Tukey post hoc. Significance levels are denoted by * $p < 0.05$, ** $p < 0.01$.

Figure 5. Peak joint velocity by preceding digit strike

The mean ($\pm$ SE) peak velocity computed across subjects for the MCP (left) and PIP (right) joints from each digit (x-axis) is plotted for each digit strike (rows) preceded by the four other digits (PreF, lines in each plot).

Figure 6. Significant interaction of GROUP*PreF on peak velocity during thumb strikes
 The mean ($\pm$ SE) peak velocity is plotted only for the thumb MCP where there was a significant interaction effect of GROUP*PreF on peak velocity as revealed by two-way ANOVAs with Tukey post hoc. Significance levels are denoted by * $p < 0.05$.

Figure 7. PC and cluster analysis

Examples are shown for covariation among MCP joints for pairs of digits during sequences where (A) thumb preceded the middle finger strike, and (B) thumb preceded the ring finger strike. The upper panel in each displays the weightings of PC1 and 2 for each subject (filled circle = professional, white = amateur) which were used in the discriminant analysis. The lower panel displays the patterns of coefficients PC1 and 2 for each finger pairing.

Table 1

Subjects' piano training and performance

Subject #	Professional /Amateur	Age (yrs)	Age training began (yrs)	# years training	Inter-keystroke Interval (IKI, ms)	MIDI velocity	Contact Duration (ms)
1	P	36	4	32	122±3	105±2	127±5
2	P	30	3	27	124±4	102±2	127±6
3	P	26	6	20	126±2	86±1	120±8
4	P	28	8	20	123±1	94±4	123±9
5	P	44	3	41	124±3	96±3	137±9
6	A	20	6	14	143±6	85±2	136±10
7	A	40	4	30	124±3	84±3	126±10
8	A	33	5	25	140±3	85±1	147±10
9	A	54	6	48	147±5	80±2	131±4
10	A	19	5	14	155±5	84±2	152±7

Values for IKI and MIDI velocity, and contact duration are mean ±SD

Table 2

Classification rates into training groups based on PCs 1-2 by central and preceding digit

	Thumb MCP PIP	Index MCP PIP	Middle MCP PIP	Ring MCP PIP	Little MCP PIP
Thumb	NA	0.3	0.8	0.3	0.9
Index	0.1	0.5	NA	0.5	0.4
Middle	0.3	0.2	0.4	0.2	NA
Ring	0.3	0	0.5	0.3	0.2
Little	0	0.6	0.7	0	0.3

Values are the ratio of correctly classified cases for each central striking digit (top) with each other digit preceding the central strike (left).

Table 3

Classification results by subject

Subject #	MCP				PIP	
	Index (pre-Little)	Middle (pre-Thumb)	Little (pre-Middle)	Ring (pre-Thumb)	Index (pre-Thumb)	Little (pre-Index)
1	A	P	P	P	P	P
2	P	A	P	P	P	P
3	A	P	P	P	A	P
4	P	P	P	P	P	A
5	P	A	A	A	P	A
6	A	A	A	A	A	A
7	A	A	P	A	A	P
8	A	A	P	A	P	A
9	P	A	A	A	A	A
10	A	A	A	A	A	A

For classifications that were 70% correct, classification of each subject is shown: P = professional; A = Amateur; bolded cases indicate misclassification.