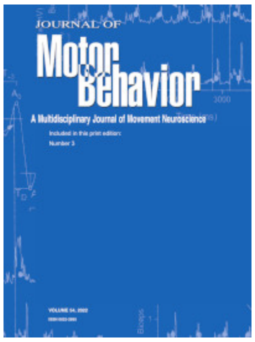

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RESEARCH ARTICLE

Proximal-to-Distal Sequences of Attack and Release Movements of Expert Pianists during Pressed-Staccato Keystrokes

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ABSTRACT. The aims of this study were to *i*) evaluate proximal-to-distal sequencing (PDS) in pianists' attack and release movements during pressed-*staccato* keystrokes, and *ii*) investigate if trunk motion facilitates PDS of upper-limb movements. Nine expert pianists performed a series of loud pressed-*staccato* keystrokes. Kinematic data was recorded with a 3 D motion capture system. PDS was assessed by comparing temporal organization of peak velocities from the pelvis to the wrist. Evidence of PDS was found across the kinematic chain. Pianists' use of PDS differed mainly between scapula and shoulder movements. Trunk motion facilitated PDS by increasing anticipatory shoulder movements and by preceding shoulder-girdle attack and release movements. Implications might relate to research on performance optimization and injury prevention strategies.

Keywords: piano performance, proximal-to-distal sequencing, trunk motion, touch, articulation

Introduction

Piano performance involves several skilled multi-joint movements. Proximal-to-distal sequencing (PDS) of multi-joint movements is described as a key feature of several motor behaviors such as hitting, throwing, and jumping (Hatsopoulos et al., 2010). This type of multi-joint movement organization has been reported in a variety of explosive sport movements [e.g., tennis serve (Elliott et al., 1995; Wagner et al., 2014), jumping (Chiu et al., 2014), baseball overarm throwing (Hirashima et al., 2002), shot put throwing (Zatsiorsky et al., 1981), and team-handball throwing (Wagner et al., 2012)], but also in artistic activities such as piano performance (Furuya & Kinoshita, 2007) and dance (Bronner & Ojofeitimi, 2006). Potential benefits of PDS relate to the summation of speed principle (where the speed of a distal segment is maximized by summing the velocity contribution of more proximal segments) and the use of motion-dependent interaction torques (i.e., torques that arise at a given joint due to the rotations of other joints) (Hirashima et al., 2003; Putnam, 1991,1993). Complementary rationales also address the existence of a proximal-to-distal transfer of momentum (de Subijana, 2010; Wang et al., 2010). Unlike sports, improvement of an artistic performance does not necessarily imply producing maximum speed at a given distal segment (e.g., to maximize ball velocity). Evidence shows that it is not the summation of speed principle but rather the use of motion-dependent interaction torques that account for the reported PDS in piano performance and dance (Bronner & Ojofeitimi, 2006; Furuya & Kinoshita, 2007). By reducing muscle-dependent torque of more distal joints, which are constantly solicited in piano playing, PDS might first help pianists maintain high levels of performance over extended periods of time. Second, as more than half of professional pianists suffers from practice-related musculoskeletal disorders (PRMDs) (Bragge et al., 2006), PDS might also help reduce exposure to risks factors of PRMDs at distal segments (i.e., overuse), where higher prevalence of injuries has been reported in pianists (Sakai, 2002).

While studies on PDS in sports generally integrate trunk motion in the analysis, only a few contributions in pianists' biomechanics have studied pelvis and thorax movements (e.g., Verdugo et al., 2019, Verdugo et al., 2020). Mainstream approaches to piano performance do not usually integrate detailed recommendations related to pelvis and thorax movements (e.g., Fink, 1992; Neuhaus, 1978). However, these movements (such as pelvis anteroposterior rotation and thorax flexion and extension) have been addressed by specific approaches (e.g., Verdugo, 2018). The only available study on pianists' PDS focuses on shoulder, elbow, and wrist movements (Furuya & Kinoshita, 2007). Unlike novice players, expert pianists exhibited a PDS organization during the attack-swing of isolated keystrokes performed with a struck touch (the attack is initiated with the fingertip at a certain distance from the key surface) and a *staccato* articulation (the key is rapidly released after the attack). Struck touch is usually opposed to pressed touch (i.e., the attack is initiated with the fingertip in contact with

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the key surface) in studies on sound control of piano tones (Goebl et al., 2005, 2014; Kinoshita et al., 2007). As pressed touch imposes higher spatiotemporal constraints than struck touch before the attack of the key (as the fingertip must remain in contact with the key before the attack), it is unclear whether expert pianists might establish a PDS organization when using a pressed touch. *Staccato* piano tones imply a fast upward (and sometimes forward) motion of the fingertip to release the key immediately after the end of the key-descent. In a previous study, we observed that the upward-forward release motion of the fingertip during isolated *staccato* keystrokes (pressed and struck) is mainly induced by shoulder-girdle joints (Verdugo et al., 2020). So far, no study has addressed PDS of this specific kind of multi-joint release motion. Addressing this gap in the literature could be highly relevant for pianists, as they commonly use a *staccato* articulation even when this type of articulation is not specified in the score (particularly when performing loud tones coupled with the use of the sustain pedal, which is an extremely common musical context in the classical piano repertoire).

The first objective of this study was to evaluate if there is a PDS organization in pianists' attack and release movements during pressed-*staccato* keystrokes, while integrating pelvis, thorax, and scapula movements in the analysis [if Hirashima et al. (2002) documented PDS of scapula and shoulder muscle activity during overarm throwing, to the best of our knowledge, there is no empirical evidence on PDS between scapula and shoulder movements in the context of either sport or artistic activities]. The second objective was to investigate if trunk motion might facilitate PDS of upper-limb movements. Based on the results of previous studies on pianists' whole-body movements while performing isolated tones (Verdugo et al., 2019, 2020), we hypothesized that pianists might establish a PDS organization while performing pressed-*staccato* keystrokes particularly when using trunk motion, which seemed to increase mobility before the attack of pressed keystrokes and anticipate the release motion of shoulder-girdle joints associated with *staccato* tones.

Materials and Methods

Participants

Nine expert pianists (2♀; 7♂; mean age 32.8 ± 3.7 years) holding or pursuing a doctoral degree in piano performance at Université de Montréal participated in the study. Experimental instructions and protocol were electronically sent to participants and each of them provided a written consent before the experience. The study was approved by the Université de Montréal Ethics Committee (No. 18-086-CPER-D).

Experimental Procedures

A set of 68 reflective markers was placed on the pelvis, thorax, right upper limb, and left lower limb (Figure 1). The marker set was based on complementary kinematic models (e.g., Cerveri et al., 2007; Jackson et al., 2012) and included anatomical markers (located on bony landmarks for the model definition) and technical markers (located in areas that minimize skin movement artifacts and marker occlusion for joint kinematics estimation). In line with previous recommendations (Begon et al., 2007; Michaud et al., 2016), two static trials and a

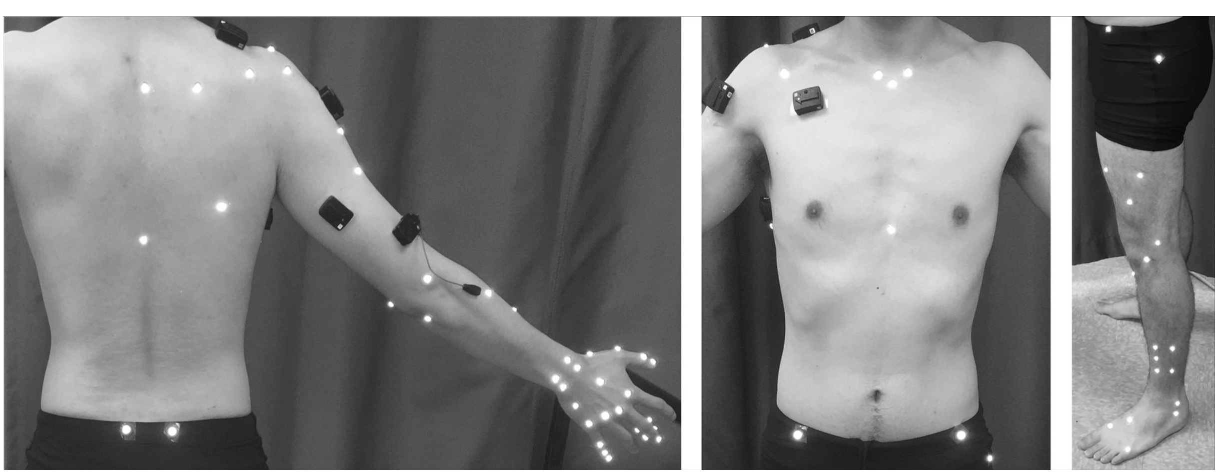

FIGURE 1. Position of the reflective markers. Note: participants also wore surface electromyographic sensors. These data are discussed in Degrave et al. (2020).

series of nine setup movements were first collected for each participant to locate joint centers and personalize a kinematic model at a later stage. Participants were then asked to perform the experimental task at the piano. The experimental task consisted of repetitive pressed-*staccato* keystrokes (A4) performed on a computer-controlled grand piano (Bösendorfer CEUS) with the middle finger of the right hand. Participants performed this task following two experimental conditions: using trunk and upper-limb movements (*whole-body* condition) and using only upper-limb movements (*upper-limb* condition). The order of conditions was randomized, and each condition accounted for 2 series of 20 keystrokes. Data from the first and last keystrokes of each 20-tone trial were excluded from the analysis (each condition accounted then for $2 \times 18 = 36$ keystrokes per participant). The tone target was set at a high sound intensity level (*forte*, 82 dB) and a fixed slow tempo (30 bpm). Three consecutive keystrokes were previously recorded on the Bösendorfer piano by one experimenter and played to the participants by the reproducing system of the piano at the beginning of the experience. Sound intensity level was monitored to inform pianists if they differed more than ± 1 dB from the target tone, and tempo was shown to participants with a metronome before the beginning of each condition. Pianists were asked to constantly hold the sustain pedal throughout each trial.

Data Collection and Processing

Three-dimensional kinematic data were collected using Nexus (version 2.6) and an 18 VICON camera motion analysis system (Oxford Metrics Ltd., Oxford, United Kingdom) at a sampling rate of 150 Hz. A digital sound-level meter (Extech 407730) placed at 1.4 meters on the right side of the piano soundboard was used to monitor sound intensity levels. The lid of the grand piano was closed to reduce marker occlusion during the experiment.

Static trials and setup movements acquired during the data collection were used to locate joint centers and to create a personalized 36 degree-of-freedom (DoF) kinematic model of each participant (pelvis, [root segment, 6 DoF; $q_{1–6}$], thorax [3 DoF; $q_{7–9}$], clavicle, scapula, and arm [3 DoF each; $q_{10–18}$], forearm and wrist [2 DoF each; $q_{19–22}$], middle finger metacarpophalangeal joint [2 DoF; $q_{23–24}$], thigh, shank, and foot [3 DoF each; $q_{25–33}$], and head [3 DoF; $q_{34–36}$]). SCoRE algorithm (Ehrig et al., 2006) was used to locate the centers of rotation of pelvo-thoracic joints and the wrist. Based on recommendations by Michaud et al. (2016), bony landmarks were used to locate sternoclavicular, acromioclavicular and glenohumeral joints. SARA algorithm (Ehrig et al., 2007) was utilized to define flexion and prosupination axes of the elbow. Generalized coordinates (**q**) of the kinematic model for each experimental trial were reconstructed by solving an inverse kinematics problem based on a weighted nonlinear least-squares algorithm (Begon et al., 2008). As in Verdugo et al. (2020), lower weightings (0.001 *vs* 1) were given to the markers placed on the middle finger to account for their sporadic occlusion produced by the fallboard of the grand piano. The reconstructed joint angles were smoothed using a 2nd order Butterworth filter with a cutoff frequency of 10 Hz.

Kinematic data were segmented using as reference the beginning of the attack phase (t_0=0 s), which was defined by comparing the vertical position of a marker placed at the fingertip in relation to a marker placed on the keyboard. The keystroke analysis window included 1000 ms before t_0 (i.e., anticipation phase) and 400 ms after t_0 (i.e., attack and release phases). Movements of the attack and release motion chains were defined based on previous studies on pianists' kinematics during isolated keystrokes (e.g., Furuya & Kinoshita, 2008; Verdugo et al., 2020) (Table 1). Motion of the metacarpophalangeal joint was not included in the analysis because its contribution to fingertip vertical velocity is rather limited during isolated keystrokes (Verdugo et al., 2020). The release chain did not include movements of the wrist and the elbow as *i*) there were no consistent release movements across participants at these joints, and *ii*) shoulder-girdle joints are the prime movers of the release motion of isolated *staccato* keystrokes (Verdugo et al., 2020). Pianists' joint motion might be rather subtle, particularly at proximal joints, and several kinematic strategies can be used to produce equivalent target tones. Therefore, a threshold was used to establish the presence/absence of the studied movements of each motion chain. This threshold was set at 10% of the highest reported velocity value for each specific movement across all participants and conditions or at a maximum threshold of 5°/s for angular velocities and 5 mm/s for scapula retraction/protraction velocity (Table 1).

PDS organization was calculated by comparing the time of occurrence of peak velocity of each adjacent joints or segment pairs (pelvis/thorax, thorax/scapula, thorax/shoulder, scapula/shoulder, shoulder/elbow, and elbow/wrist) (Furuya & Kinoshita, 2007; Putnam, 1993; Wagner et al., 2014). Angular velocities were computed using a three-point finite difference. Since scapula protraction/retraction is the result of scapula and clavicle rotations and does not necessarily occur in the sagittal plane, its velocity was estimated by calculating the angular contribution of the scapula and clavicle DoFs to the anteroposterior velocity of the shoulder joint center. Computed as the partial derivate with respect to the generalized coordinates, the shoulder joint center velocity $(\dot{M})$ can be expressed as the sum of the contributions of each DoF of the kinematic chain (Begon et al., 2010; Verdugo et al., 2020):

TABLE 1. Mean and standard deviation of peak velocities of the attack and release motion chains.

		Whole-body condition	Upper-limb condition	Threshold
Attack motion chain				
Pelvis posterior rotation	°/s	15.77 ±6.39	—	2.78
Thorax flexion	°/s	21.08 ±9.48	—	4.57
Scapula retraction	mm/s	24.58 ±18.11	12.76 ±5.84	5.00
Shoulder adduction	°/s	22.83 ±17.22	14.67 ±7.47	5.00
Shoulder extension	°/s	14.14 ±6.36	7.96 ±4.22	3.38
Elbow extension	°/s	62.09 ±30.99	73.15 ±40.18	5.00
Wrist flexion	°/s	291.83 ±108.04	264.09 ±81.28	5.00
Release motion chain				
Pelvis anterior rotation	°/s	29.87 ±22.96	—	5.00
Thorax extension	°/s	41.23 ±35.84	—	5.00
Scapula protraction	mm/s	52.90 ±34.38	55.04 ±35.94	5.00
Shoulder abduction	°/s	42.43 ±23.43	38.76 ±18.33	5.00
Shoulder flexion	°/s	49.58 ±32.11	56.11 ±28.16	5.00

The column Threshold indicates the velocity threshold used to establish presence/absence of movements during each keystroke.

$$\dot{\boldsymbol{M}} = \underbrace{\frac{\partial \boldsymbol{M}}{\partial \boldsymbol{q}_{1-6}}\dot{\boldsymbol{q}}_{1-6}}_{\textit{Pelvis contribution}} + \underbrace{\frac{\partial \boldsymbol{M}}{\partial \boldsymbol{q}_{7-9}}\dot{\boldsymbol{q}}_{7-9}}_{\textit{Thorax contribution}} + \underbrace{\frac{\partial \boldsymbol{M}}{\partial \boldsymbol{q}_{10-15}}\dot{\boldsymbol{q}}_{10-15}}_{\textit{Scapula/clavicle contribution}} \tag{1}$$

Statistical Analysis

PDS organization was evaluated using two methods. On the one hand, adjacent movement pairs of each keystroke (e.g., pelvic posterior rotation and thorax flexion, thorax flexion and scapula retraction, etc.) were evaluated in terms of *i*) presence/absence of movement (absence was reported when one or both movements were not observed) and *ii*) presence/absence of PDS (absence was associated with simultaneous organization, distal-to-proximal sequencing, and absence of one or both movements). Percentages of movement presence and PDS presence were computed for each participant in each condition (100% of each condition being 36 keystrokes). Wilcoxon signed rank tests ($N = 9$) were used to estimate if percentages of PDS presence were smaller than percentages of movement presence (no statistical test was performed if percentages of PDS presence and movement presence were identical). On the other hand, we used Wilcoxon signed rank tests to compare mean time values of peak velocity of participants that performed the respective movements (no statistical test was executed for comparisons that exhibited $N < 5$). To evaluate if trunk motion facilitates PDS of upper-limb movements, we computed Wilcoxon signed rank tests ($N = 9$) on percentage data of the experimental conditions: *whole-body* versus *upper-limb* condition. *p*-Values were computed using the exact method. Significance was set at $p < 0.05$ and the false discovery rate (FDR) (Benjamini & Hochberg, 1995) procedure was applied to control for potential errors produced by multiple comparisons ($q = 0.05$; FDR = 5%). Two-tailed tests were used for most comparisons except when differences could exist in only one direction (one-tailed tests): *i*) comparisons of percentages of PDS presence and movement presence (PDS presence can only be equal or smaller than movement presence), and *ii*) comparisons of mean time values of movement pairs that exhibited identical percentages of PDS presence and movements presence (PDS of mean time values being the only plausible prediction to be tested). Data processing and statistical analyses were performed using Matlab R2019b (The MathWorks Inc., Natick, MA, USA).

Results

When movements were found, time-history velocity values across participants depicted a PDS organization, i.e., the proximal movement decelerated while the distal movement accelerated (Figure 2). This was however not the case of the scapula/shoulder pairs since their velocities increased and decreased during analogous time periods. Time-history velocities of scapula retraction and shoulder extension during the attack chain of the *upper-limb* condition were limited (Figure 2) and their mean peak velocities showed the smallest values across conditions and motion chains (scapula

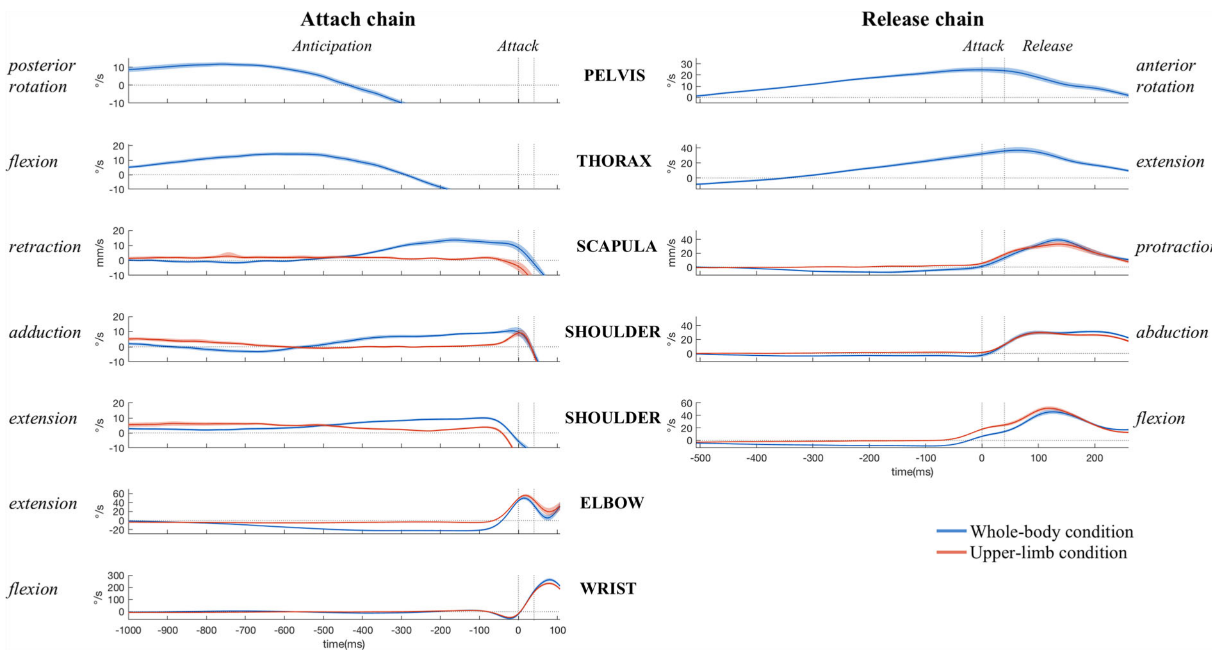

FIGURE 2. Mean (plain lines) and 95% bootstrap confidence intervals (shaded areas) of time-history velocity values across participants of the movements of the attack (left panels) and release (right panels) motion chains. Mean and 95% bootstrap confidence intervals were computed with the data of all keystrokes where the movements were reported. Horizontal dotted lines serve to better visualize positive and negative velocity values (the movement descriptors specified in the figure relate to positive velocity values). Vertical dotted lines indicate the moment of the beginning of the attack (t_0=0) and an estimation of the end of the key descent based on the keystroke timing data of loud pressed keystrokes reported in Goebl et al. (2005) and Verdugo et al. (2020).

retraction = 12.76 ± 5.84 mm/s, shoulder extension = 7.96 ± 4.22 °/s) (Table 1).

The presence of movements according to our threshold increased in a proximal-distal rationale during the attack chain (Figure 3), whereas they were practically always present during the release chain (Figure 4). No significant differences were found between PDS presence and movement presence during the attack chain. Apart from scapula/shoulder pairs, PDS presence and movement presence were overall similar or identical (Figure 3). In the release chain, PDS presence was generally less important than movement presence (Figure 4). Significant differences were found at different movement pairs of the *whole-body* condition [thorax-extension/scapula-protraction ($q = 0.047$); thorax-extension/shoulder-flexion ($q = 0.031$); scapula-protraction/shoulder-abduction ($q = 0.012$); scapula-protraction/shoulder-flexion ($q = 0.012$)] and the *upper-limb* condition [scapula-protraction/shoulder-abduction ($q = 0.008$); scapula-protraction/shoulder-flexion ($q = 0.008$)].

As shown in Figure 5, participants' mean time values of peak velocity showed a proximal-to-distal organization at most movement pairs of the attack and release chains. This was however not the case for scapula/shoulder comparisons, as participants mean time values showed proximal-to-distal and distal-to-proximal organizations. Apart from scapula/shoulder pairs, significant PDS was found across the whole kinematic chain during the *whole-body* condition and at the elbow-extension/wrist-flexion comparison of the *upper-limb* condition (see Table 2 for detailed results of statistical tests). Due to a limited number of data points ($N < 5$), no statistical test was performed in four cases of the attack chain [*whole-body* condition: pelvis-posterior-rotation/thorax-flexion ($N = 4$); *upper-limb* condition: scapula-retraction/shoulder-adduction ($N = 3$), scapula-retraction/shoulder-extension ($N = 2$), shoulder-extension/elbow-extension ($N = 3$)].

In the attack chain, mean percentages across participants of movement presence and PDS presence of scapula/shoulder and shoulder/elbow pairs showed overall higher values in the *whole-body* than in the *upper-limb* condition (Figure 3). Only movement presence of shoulder-extension/elbow-extension exhibited a significant difference between the two conditions ($q = 0.031$). At the elbow/wrist pair, participants showed practically identical

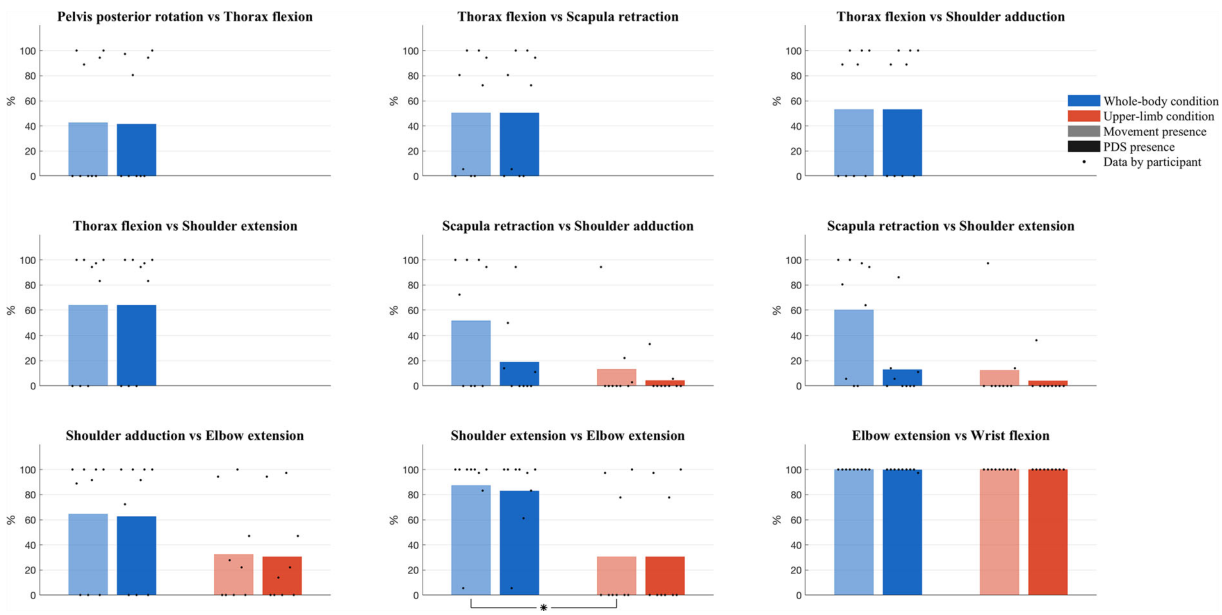

FIGURE 3. Attack chain: presence of the selected movements (transparent bars) and of proximal-to-distal sequencing (full bars) by each experimental condition. Single and double asterisks represent significant differences between percentage values: $*q < 0.05$, $**q < 0.01$. p-Values were corrected (q value) with the false discovery rate procedure for multiple comparisons ($q < 0.05$).

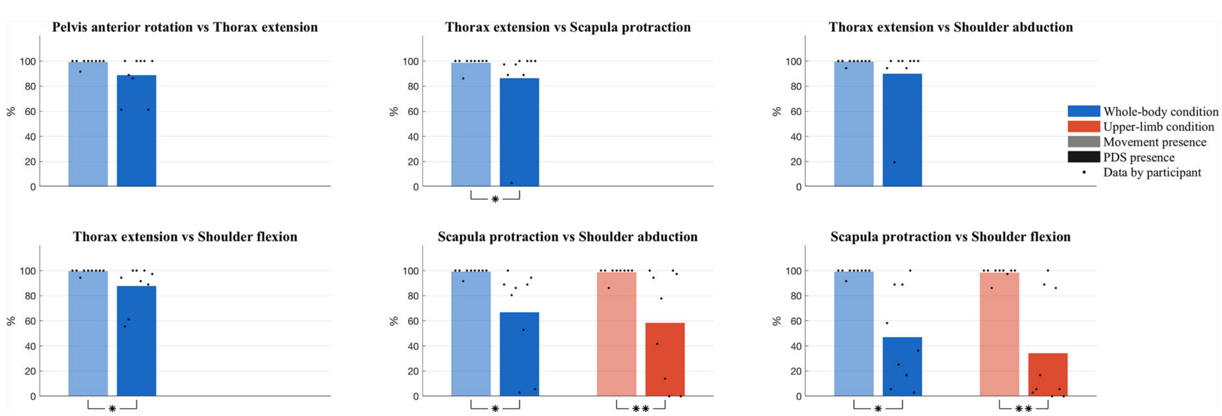

FIGURE 4. Release chain: presence of the selected movements (transparent bars) and of proximal-to-distal sequencing (full bars) by each experimental condition. Single and double asterisks represent significant differences between percentage values: $*q < 0.05$, $**q < 0.01$. p-Values were corrected (q value) with the false discovery rate procedure for multiple comparisons ($q < 0.05$).

percentages (100%, and 97% in only one case) of movement presence and PDS presence during both conditions (Figure 3). In the release chain, no significant differences were found between movement presence and PDS presence of scapula/shoulder pairs of the *whole-body* and the *upper-limb* condition (Figure 4).

Discussion

In this study, we evaluated expert pianists' PDS of key-attack and key-release movements during isolated pressed-*staccato* keystrokes by analyzing the temporal organization of peak velocities from the pelvis to the wrist. In addition, we examined the impact of trunk

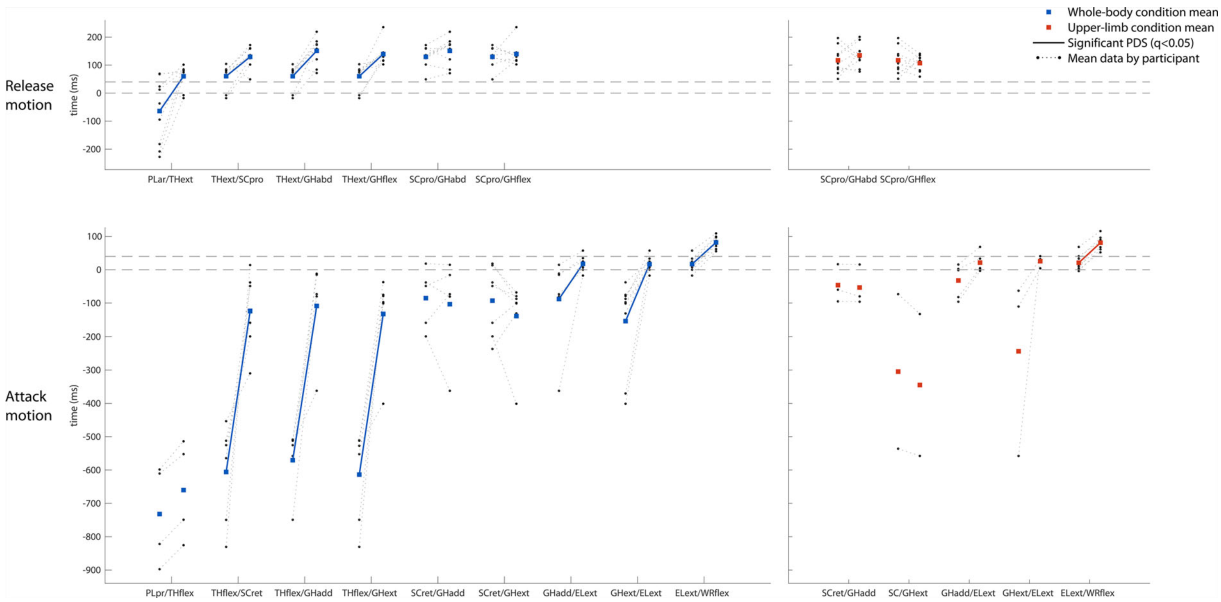

FIGURE 5. Temporal organization of peak velocities during the attack and release motion chains by each experimental condition. Solid lines linking mean time values across participants illustrate a significant proximal-to-distal sequencing (no statistical test was executed for comparisons that exhibited $N < 5$). Horizontal dotted lines indicate the moment of the beginning of the attack (t_0=0) and an estimation of the end of the key descent (see caption of Figure 2). PLpr = pelvis posterior rotation; PLar = pelvis anterior rotation; THflex = thorax flexion; THext = thorax extension; SCret = scapula retraction; SCpro = scapula protraction; GHadd = shoulder adduction; GHabd = shoulder abduction; GHext = shoulder extension; GHflex = shoulder flexion; ELext = elbow extension; WRflex = wrist flexion.

motion on PDS of upper-limb movements. Our results indicated the presence of PDS during both attack and release multi-joint motion chains. Pianists' use of PDS was however less clear between movements of the scapula and the shoulder, where pianists showed signs of both PDS and distal-to-proximal sequencing. Pelvis and thorax movements contributed to PDS of upper-limb movements by facilitating shoulder-girdle movements, particularly shoulder extension, during the anticipation phase of pressed keystrokes. In addition, trunk motion anticipated shoulder-girdle movements during both attack and release chains.

Proximal-to-Distal Sequencing: Key Attack

Compared to struck touch, where the hand can be freely lifted over the keyboard before the attack, pressed touch imposes greater spatiotemporal constraints because the fingertip must remain in contact with the key before initiating the attack. Pressed touch is however an important feature of piano performance, as it facilitates sound control by generating a smoother key-descent acceleration than struck touch (Goebl et al., 2005). Despite greater spatiotemporal constraints of pressed touch before the attack, we found PDS of shoulder extension, elbow extension, and wrist flexion during the key-attack motion chain as in the case of struck touch reported in Furuya and Kinoshita (2007) (when these movements were performed, they practically always showed PDS). In addition, we found that when performed, shoulder adduction also preceded elbow extension. This indicates that potential interactions between shoulder, elbow, and wrist movements before the attack could involve not only shoulder extension, as shown by Furuya and Kinoshita (2007), but a complex downward anticipatory swing including simultaneously shoulder extension and adduction.

Movements of shoulder-girdle joints were preceded by pelvis posterior rotation and thorax flexion early during the anticipation phase. Our findings revealed significant PDS of thorax/scapula and thorax/shoulder anticipatory movements, suggesting the presence of a rationalized temporal motion organization of thorax and upper-limb movements. Trunk movements occurred however early during the anticipation phase. Mean timing differences across participants between thorax and shoulder-girdle peak velocities (thorax-flexion/scapula-retraction = 482 ms; thorax-flexion/shoulder-adduction = 462 ms; thorax-flexion/shoulder-extension = 481 ms; see Figure 5) were larger than those reported in several sports (smaller than 100 ms, see, e.g., Wagner et al., 2014). These larger timing differences in pianists than in athletes might relate

TABLE 2. Results of the Wilcoxon signed rank tests performed on participants' mean time values of peak velocity of movements of the attack and release motion chains.

	N	PDS%	*q*	Participants								
Attack motion: Whole-body condition												
Pelvis post. rot. / Thorax flexion	4	100	–		2		4				8	9
Thorax flexion / Scapula retraction	6	100	**0.031**		2	3	4			7	8	9
Thorax flexion / Shoulder adduction	5	100	**0.042**		2		4		6	7		9
Thorax flexion / Shoulder extension	6	100	**0.031**		2		4		6	7	8	9
Scapula retraction / Shoulder adduction	5	40	0.813	1	2		4			7		9
Scapula retraction / Shoulder extension	7	29	0.429	1	2	3	4			7	8	9
Shoulder adduction / Elbow extension	6	100	**0.042**	1	2		4		6	7		9
Shoulder extension / Elbow extension	9	100	**0.016**	1	2	3	4	5	6	7	8	9
Elbow extension / Wrist flexion	9	100	**0.016**	1	2	3	4	5	6	7	8	9
Attack motion: Upper-limb condition												
Scapula retraction / Shoulder adduction	3	0	–	1						7		9
Scapula retraction / Shoulder extension	2	0	–		2							9
Shoulder adduction / Elbow extension	5	100	0.063	1			4		6	7		9
Shoulder extension / Elbow extension	3	100	–		2				6			9
Elbow extension / Wrist flexion	9	100	**0.004**	1	2	3	4	5	6	7	8	9
Release motion: Whole-body condition												
Pelvis ant. rot. / Thorax extension	9	100	**0.012**	1	2	3	4	5	6	7	8	9
Thorax extension / Scapula protraction	9	89	**0.018**	1	2	3	4	5	6	7	8	9
Thorax extension / Shoulder abduction	9	89	**0.016**	1	2	3	4	5	6	7	8	9
Thorax extension / Shoulder flexion	9	100	**0.012**	1	2	3	4	5	6	7	8	9
Scapula protraction / Shoulder abduction	9	67	0.084	1	2	3	4	5	6	7	8	9
Scapula protraction / Shoulder flexion	9	44	0.820	1	2	3	4	5	6	7	8	9
Release motion: Upper-limb condition												
Scapula protraction / Shoulder abduction	9	56	0.652	1	2	3	4	5	6	7	8	9
Scapula protraction / Shoulder flexion	9	33	0.652	1	2	3	4	5	6	7	8	9

p-Values were corrected (*q* value) with the false discovery rate procedure for multiple comparisons ($q < 0.05$). Bold *q*-values illustrate a significant proximal-to-distal sequencing. The column *N* indicates the number of participants used in the analysis (no test was performed when $N < 5$). The column %PDS shows the percentage of participants that exhibited a proximal-to-distal organization of the respective comparisons of mean time values. The column Participants indicates pianists where data was found to perform the analysis. Bold *d* values illustrate a significant proximal-to-distal sequencing.

to the low intensity character of piano performance compared to explosive sport activities. Nonetheless, actual interactions between anticipatory thorax and shoulder-girdle movements should be tested by future research focusing on kinetic analysis of piano performance.

Proximal-to-Distal Sequencing: Key Release

Our results showed a PDS of pelvis, thorax, and shoulder-girdle movements during the release motion chain in the *whole-body* condition. Specifically, pelvis anterior rotation preceded thorax extension and thorax extension preceded scapula protraction and shoulder flexion/abduction. Timing differences between thorax and shoulder-girdle movements were smaller than 100 ms (thorax-extension/scapula-protraction = 69 ms; thorax-extension/shoulder-abduction = 91 ms; thorax-extension/shoulder-flexion = 79 ms; see Figure 5). These findings indicate a more similar PDS of pianists' release proximal movements in relation to explosive sports activities (Wagner et al., 2014) than anticipatory proximal movements. Shorter time differences between thorax and shoulder-girdle movements were coupled with faster shoulder-girdle movements during the release motion chain, as mean velocities were at least twice as fast compared to the attack chain in both *whole-body* and *upper-limb* conditions (see Table 1). In a previous study, we found that the release motion of *staccato* keystrokes induced an activation burst of shoulder muscles during and after the attack (Degrave et al., 2020). The presented PDS of thorax and shoulder-girdle release movements should therefore be further investigated by evaluating if motion-dependent interaction torques might effectively occur between these movements and modify shoulder muscle load during the production of loud *staccato* tones. Similar temporal sequencing of thorax extension and shoulder-girdle movements could be investigated in other musical activities that involve a burst of shoulder muscle activations, such as the up-bow phase of the violin bowing movement (Shan et al., 2004).

By using multi-joint movements, pianists modulate not only hand and fingertip velocities but also the effective mass applied to the key (Kinoshita et al., 2007), which can involve the mass of the hand, forearm, arm, and torso. Evidence shows that expert pianists mobilize the mass of the arm and torso in a forward rather than downward direction during the key descent by using respectively *i*) shoulder flexion and scapula protraction and *ii*) pelvis anterior rotation (Furuya & Kinoshita, 2008; Verdugo et al., 2020). Therefore, these movements, which contribute to the production of PDS of the key-release motion chain, play also a central role during the key-attack by controlling the keystroke effective mass and, consequently, the targeted key velocity and tone intensity.

Effect of Trunk Motion

Temporal organization of multi-joint movements depends not only on expertise but also on the specific characteristics of the task performed (Wagner et al., 2012). Our results showed that expert pianists did not always perform the anticipatory movements of shoulder-girdle joints. Mean presence of scapula and shoulder anticipatory movements (attack chain) was overall higher during the *whole-body* condition, and a significant difference was found specifically at the shoulder-extension/elbow-extension pair (shoulder-girdle anticipatory movements also exhibited faster mean peak velocity values when the trunk was mobilized as shown in Table 1). Thoracic posture affects shoulder range of motion in standing (Barrett et al., 2016) and sitting positions (Kanlayanaphotporn, 2014; Kebaetse et al., 1999). In our study, pianists increased mobility of shoulder-girdle joints before the attack by using pelvis posterior rotation and thorax flexion, which facilitated an anticipatory shoulder downswing usually not related to pressed touch but to struck touch in studies on pianists' motor behavior (Furuya et al., 2010). Indeed, according to the cited study, contrary to struck touch (which exhibited use of proximal-to-distal inter-segmental dynamics), pressed touch was characterized by effective utilization of distal-to-proximal inter-segmental dynamics. The authors hypothesized that this difference was due to the stronger spatiotemporal constrains of pressed touch, which requires instantaneous acceleration at the limb endpoint to produce the targeted key velocity. Our findings show that trunk motion helps pianists mitigate the increased spatiotemporal constraints of pressed touch by facilitating shoulder movements before the attack (even if the fingertip must remain in contact with the key). Therefore, a comprehensive kinetic study of pressed touch, which includes in the analysis the utilization of trunk movement, would be necessary to develop a deeper understanding of the complex motion interactions that might occur while producing pressed keystrokes. Anticipatory trunk and shoulder-girdle movements were however inconsistent across participants in both *upper-limb* and *whole-body* conditions (see, e.g., Table 2). We hypothesize that this inconsistency might be due to the greater attention of piano performance approaches to attack and release movements compared to proximal anticipatory movements (see, e.g., Fink, 1992; Neuhaus, 1978).

Scapula and Shoulder Temporal Movement Organization

Scapula and shoulder movements showed different temporal organizations of peak velocities across participants: they exhibited the smallest percentage of PDS presence (Figures 3 and 4) and presented PDS and distal-to-proximal sequencing of mean time values of peak velocity (Figure 5). Some approaches to piano performance address shoulder-girdle movements (see, e.g., Fink, 1992; Verdugo, 2018). However, visual observation of scapula movements is challenging (Ellenbecker et al., 2012), making it difficult for pianists to accurately evaluate these movements in the context of practice sessions or instrumental lessons. If some participants performed PDS between scapula and shoulder movements, mean time-history velocity values across participants (Figure 2) depicted similar timing of both movement initiation and acceleration/deceleration periods [kinematic characteristics that differ from theoretical descriptions of PDS (Putnam, 1993)]. To the best of our knowledge, there is no previous evidence of PDS between scapula and shoulder movements. Further research is therefore necessary to develop a deeper understanding of the reported temporal organizations of scapula and shoulder movements and their potential effect on shoulder muscle load during piano performance.

Limitations and Future Research

This study addressed PDS of pianists' attack and release movements of trunk and upper-limb joints. Due to limited empirical evidence on this research topic, the experimental protocol focused on isolated keystrokes to standardize performance parameters affecting pianists' movements. Our findings could be tested on actual musical excerpts, and studies based on a larger sample size could highlight the scope of the presented results. PDS was evaluated by assessing timing of peak velocities. Future studies might also assess timing of movement initiation to gain further knowledge on temporal organization of pianists' whole-body movements. In addition, presence of PDS does not necessarily involves effective utilization of motion-dependent interaction torques. If the present study sheds light on the possibility of expert pianists to use PDS in the context of pressed-

staccato keystrokes, actual impact of this type of strategy on motion-dependent and muscular torques should be addressed by future research.

Conclusion

By analyzing temporal sequencing of pianists' movements, this study showed the presence of PDS from the pelvis to the wrist during the attack and release movements of pressed-*staccato* isolated keystrokes. The use of PDS between scapula and shoulder movements was less obvious, as pianists exhibited different temporal organizations between these movements. We also showed that trunk motion facilitated PDS of pressed-*staccato* keystrokes. On the one hand, it increased mobility of shoulder-girdle joints during the anticipatory keystroke swing, thus mitigating motion constraints related to pressed touch. On the other hand, it preceded the fast upward thrust of shoulder-girdle joints associated with *staccato* and loud tones. Our study contributes to a better understanding of expert pianists' multi-joint temporal organization of key-attack and key-release movements. Implications relate to research on performance optimization and injury prevention strategies.

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Disclosure statement

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