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16

1 Proximal-to-distal Sequences of Attack and Release Movements of 2 Expert Pianists during Pressed-Staccato Keystrokes

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

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

16 Introduction

17 Piano performance involves several skilled multi-joint movements. Proximal-to-distal
18 sequencing (PDS) of multi-joint movements is described as a key feature of several
19 motor behaviours such as hitting, throwing, and jumping (Hatsopoulos et al., 2010).
20 This type of multi-joint movement organization has been reported in a variety of
21 explosive sport movements [*e.g.* tennis serve (Elliott et al., 1995; Wagner et al., 2014),
22 jumping (Chiu et al., 2014), baseball overarm throwing (Hirashima et al., 2002), shot
23 put throwing (Zatsiorsky et al., 1981), and team-handball throwing (Wagner et al.,
24 2012)], but also in artistic activities such as piano performance (Furuya and Kinoshita,
25 2007) and dance (Bronner and Ojofeitimi, 2006). Potential benefits of PDS relate to the
26 summation of speed principle (where the speed of a distal segment is maximized by
27 summing the velocity contribution of more proximal segments) and the use of motion-
28 dependent interaction torques (*i.e.* torques that arise at a given joint due to the rotations

1 of other joints) (Hirashima et al., 2003; Putnam, 1991,1993). Complementary rationales
2 also address the existence of a proximal-to-distal transfer of momentum (Subijana,
3 2010; Wang et al., 2010). Unlike sports, improvement of an artistic performance does
4 not necessarily imply producing maximum speed at a given distal segment (*e.g.* to
5 maximize ball velocity). Evidence shows that it is not the summation of speed principle
6 but rather the use of motion-dependent interaction torques that account for the reported
7 PDS in piano performance and dance (Bronner and Ojofeitimi, 2006; Furuya and
8 Kinoshita, 2007). By reducing muscle-dependent torque of more distal joints, which are
9 constantly solicited in piano playing, PDS might first help pianists maintain high levels
10 of performance over extended periods of time. Second, as more than half of professional
11 pianists suffers from practice-related musculoskeletal disorders (PRMDs) (Bragge et al.,
12 2006), PDS might also help reduce exposure to risks factors of PRMDs at distal
13 segments (*i.e.* overuse), where higher prevalence of injuries has been reported in
14 pianists (Sakai, 2002).

15 While studies on PDS in sports generally integrate trunk motion in the analysis,
16 only a few contributions in pianists' biomechanics have studied pelvis and thorax
17 movements (*e.g.* Verdugo et al., 2019, Verdugo et al., 2020). Mainstream approaches to
18 piano performance do not usually integrate detailed recommendations related to pelvis
19 and thorax movements (*e.g.* Fink, 1992; Neuhaus, 1978). However, these movements
20 (such as pelvis anteroposterior rotation and thorax flexion and extension) have been
21 addressed by specific approaches (*e.g.* Verdugo, 2018). The only available study on
22 pianists' PDS focuses on shoulder, elbow, and wrist movements (Furuya and Kinoshita,
23 2007). Unlike novice players, expert pianists exhibited a PDS organization during the
24 attack-swing of isolated keystrokes performed with a struck touch (the attack is initiated
25 with the fingertip at a certain distance from the key surface) and a *staccato* articulation

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

17 The first objective of this study was to evaluate if there is a PDS organization in
18 pianists' attack and release movements during pressed-*staccato* keystrokes, while
19 integrating pelvis, thorax, and scapula movements in the analysis [if
20 Hirashima et al. (2002) documented PDS of scapula and shoulder muscle activity during
21 overarm throwing, to the best of our knowledge, there is no empirical evidence on PDS
22 between scapula and shoulder movements in the context of either sport or artistic
23 activities]. The second objective was to investigate if trunk motion might facilitate PDS
24 of upper-limb movements. Based on the results of previous studies on pianists' whole-
25 body movements while performing isolated tones (Verdugo et al. 2019, 2020), we

1 hypothesized that pianists might establish a PDS organization while performing
2 pressed-*staccato* keystrokes particularly when using trunk motion, which seemed to
3 increase mobility before the attack of pressed keystrokes and anticipate the release
4 motion of shoulder-girdle joints associated with *staccato* tones.

5 **Materials and Methods**

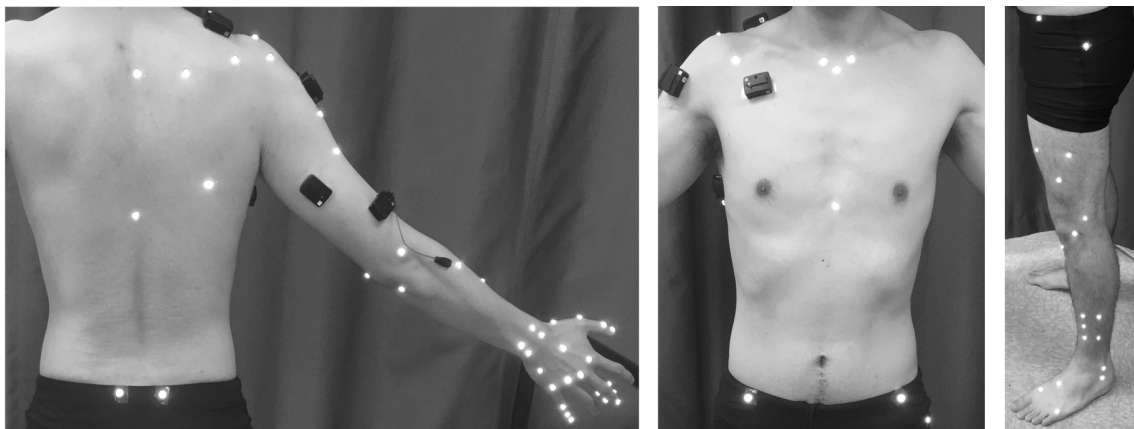
6 ***Participants***

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

12 ***Experimental Procedures***

13 A set of 68 reflective markers was placed on the pelvis, thorax, right upper limb, and
14 left lower limb (Fig. 1). The marker set was based on complementary kinematic models
15 (e.g. Cerveri et al., 2007; Jackson et al., 2012) and included anatomical markers (located
16 on bony landmarks for the model definition) and technical markers (located in areas that
17 minimize skin movement artifacts and marker occlusion for joint kinematics
18 estimation). In line with previous recommendations (Begon et al. 2007; Michaud et al.,
19 2016), two static trials and a series of nine setup movements were first collected for
20 each participant to locate joint centers and personalize a kinematic model at a later
21 stage. Participants were then asked to perform the experimental task at the piano. The
22 experimental task consisted of repetitive pressed-*staccato* keystrokes (A4) performed on
23 a computer-controlled grand piano (Bösendorfer CEUS) with the middle finger of the
24 right hand. Participants performed this task following two experimental conditions:

1 using trunk and upper-limb movements (*whole-body* condition) and using only upper-
2 limb movements (*upper-limb* condition). The order of conditions was randomized, and
3 each condition accounted for 2 series of 20 keystrokes. Data from the first and last
4 keystrokes of each 20-tone trial were excluded from the analysis (each condition
5 accounted then for $2 \times 18 = 36$ keystrokes per participant). The tone target was set at a
6 high sound intensity level (*forte*, 82 dB) and a fixed slow tempo (30 bpm). Three
7 consecutive keystrokes were previously recorded on the Bösendorfer piano by one
8 experimenter and played to the participants by the reproducing system of the piano at
9 the beginning of the experience. Sound intensity level was monitored to inform pianists
10 if they differed more than ± 1 dB from the target tone, and tempo was shown to
11 participants with a metronome before the beginning of each condition. Pianists were
12 asked to constantly hold the sustain pedal throughout each trial.



13
14 Figure 1. Position of the reflective markers. Note: participants also wore surface
15 electromyographic sensors. These data are discussed in Degraeve et al. (2020).

16

17 ***Data Collection and Processing***

18 Three-dimensional kinematic data were collected using Nexus (version 2.6) and an
19 18 VICON camera motion analysis system (Oxford Metrics Ltd., Oxford, United
20 Kingdom) at a sampling rate of 150 Hz. A digital sound-level meter (Extech 407730)

1 placed at 1.4 meters on the right side of the piano soundboard was used to monitor
2 sound intensity levels. The lid of the grand piano was closed to reduce marker occlusion
3 during the experiment.

4 Static trials and setup movements acquired during the data collection were used
5 to locate joint centers and to create a personalized 36 degree-of-freedom (DoF)
6 kinematic model of each participant (pelvis, [root segment, 6 DoF; q_{1-6}], thorax [3 DoF;
7 q_{7-9}], clavicle, scapula, and arm [3 DoF each; q_{10-18}], forearm and wrist [2 DoF each; q_{19-}
8 22], middle finger metacarpophalangeal joint [2 DoF; q_{23-24}], thigh, shank, and foot
9 [3 DoF each; q_{25-33}], and head [3 DoF; q_{34-36}). SCoRE algorithm (Ehrig et al., 2006)
10 was used to locate the centers of rotation of pelvo-thoracic joints and the wrist. Based
11 on recommendations by Michaud et al. (2016), bony landmarks were used to locate
12 sternoclavicular, acromioclavicular and glenohumeral joints. SARA algorithm (Ehrig et
13 al., 2007) was utilized to define flexion and prosupination axes of the elbow.
14 Generalized coordinates (\mathbf{q}) of the kinematic model for each experimental trial were
15 reconstructed by solving an inverse kinematics problem based on a weighted nonlinear
16 least-squares algorithm (Begon et al., 2008). As in Verdugo et al. (2020), lower
17 weightings (0.001 vs 1) were given to the markers placed on the middle finger to
18 account for their sporadic occlusion produced by the fallboard of the grand piano. The
19 reconstructed joint angles were smoothed using a 2nd order Butterworth filter with a cut-
20 off frequency of 10 Hz.

21 Kinematic data were segmented using as reference the beginning of the attack
22 phase ($t_0=0$ s), which was defined by comparing the vertical position of a marker placed
23 at the fingertip in relation to a marker placed on the keyboard. The keystroke analysis
24 window included 1000 ms before t_0 (*i.e.* anticipation phase) and 400 ms after t_0 (*i.e.*
25 attack and release phases). Movements of the attack and release motion chains were

1 defined based on previous studies on pianists' kinematics during isolated keystrokes
2 (e.g. Furuya and Kinoshita, 2008; Verdugo et al., 2020) (Table 1). Motion of the
3 metacarpophalangeal joint was not included in the analysis because its contribution to
4 fingertip vertical velocity is rather limited during isolated keystrokes (Verdugo et al.,
5 2020). The release chain did not include movements of the wrist and the elbow as
6 *i)* there were no consistent release movements across participants at these joints, and
7 *ii)* shoulder-girdle joints are the prime movers of the release motion of isolated *staccato*
8 keystrokes (Verdugo et al., 2020). Pianists' joint motion might be rather subtle,
9 particularly at proximal joints, and several kinematic strategies can be used to produce
10 equivalent target tones. Therefore, a threshold was used to establish the
11 presence/absence of the studied movements of each motion chain. This threshold was
12 set at 10% of the highest reported velocity value for each specific movement across all
13 participants and conditions or at a maximum threshold of 5°/s for angular velocities and
14 5 mm/s for scapula retraction/protraction velocity (Table 1).

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

$$\dot{M} = \underbrace{\frac{\partial M}{\partial q_{1-6}} \dot{q}_{1-6}}_{\text{Pelvis contribution}} + \underbrace{\frac{\partial M}{\partial q_{7-9}} \dot{q}_{7-9}}_{\text{Thorax contribution}} + \underbrace{\frac{\partial M}{\partial q_{10-15}} \dot{q}_{10-15}}_{\text{Scapula/clavicle contribution}} \quad (1)$$

2 Table 1. Mean and standard deviation of peak velocities of the attack and release motion
 3 chains. The column Threshold indicates the velocity threshold used to establish
 4 presence/absence of movements during each keystroke.

		<u>Whole-body condition</u>	<u>Upper-limb condition</u>	<u>Threshold</u>
<u>Attack motion chain</u>				
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
<u>Release motion chain</u>				
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

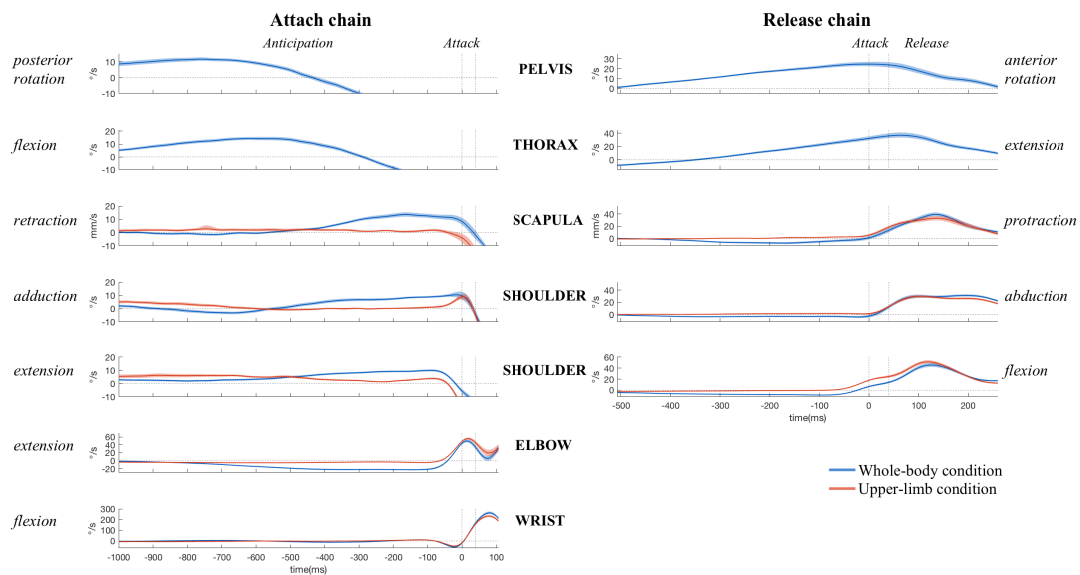
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6 ***Statistical Analysis***

7 PDS organization was evaluated using two methods. On the one hand, adjacent
 8 movement pairs of each keystroke (*e.g.*, pelvic posterior rotation and thorax flexion,
 9 thorax flexion and scapula retraction, etc.) were evaluated in terms of
 10 *i*) presence/absence of movement (absence was reported when one or both movements
 11 were not observed) and *ii*) presence/absence of PDS (absence was associated with
 12 simultaneous organization, distal-to-proximal sequencing, and absence of one or both

1 movements). Percentages of movement presence and PDS presence were computed for
2 each participant in each condition (100% of each condition being 36 keystrokes).
3 Wilcoxon signed rank tests (N=9) were used to estimate if percentages of PDS presence
4 were smaller than percentages of movement presence (no statistical test was performed
5 if percentages of PDS presence and movement presence were identical). On the other
6 hand, we used Wilcoxon signed rank tests to compare mean time values of peak
7 velocity of participants that performed the respective movements (no statistical test was
8 executed for comparisons that exhibited $N < 5$). To evaluate if trunk motion facilitates
9 PDS of upper-limb movements, we computed Wilcoxon signed rank tests (N=9) on
10 percentage data of the experimental conditions: *whole-body* versus *upper-limb*
11 condition.

12 p-Values were computed using the exact method. Significance was set at $p < 0.05$ and
13 the false discovery rate (FDR) (Benjamini and Hochberg, 1995) procedure was applied
14 to control for potential errors produced by multiple comparisons ($q = 0.05$; FDR = 5%).
15 Two-tailed tests were used for most comparisons except when differences could exist in
16 only one direction (one-tailed tests): *i*) comparisons of percentages of PDS presence and
17 movement presence (PDS presence can only be equal or smaller than movement
18 presence), and *ii*) comparisons of mean time values of movement pairs that exhibited
19 identical percentages of PDS presence and movements presence (PDS of mean time
20 values being the only plausible prediction to be tested). Data processing and statistical
21 analyses were performed using Matlab R2019b (The MathWorks Inc., Natick, MA,
22 USA).

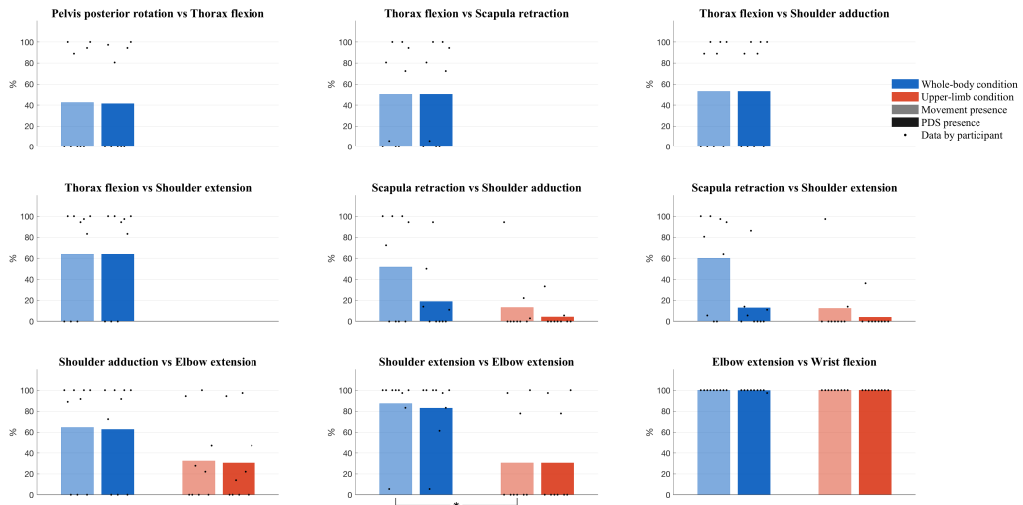


1
2 Figure 2. Mean (plain lines) and 95% bootstrap confidence intervals (shaded areas) of
3 time-history velocity values across participants of the movements of the attack (left
4 panels) and release (right panels) motion chains. Mean and 95% bootstrap confidence
5 intervals were computed with the data of all keystrokes where the movements were
6 reported. Horizontal dotted lines serve to better visualize positive and negative velocity
7 values (the movement descriptors specified in the figure relate to positive velocity
8 values). Vertical dotted lines indicate the moment of the beginning of the attack ($t_0=0$)
9 and an estimation of the end of the key descent based on the keystroke timing data of
10 loud pressed keystrokes reported in Goebel et al. (2005) and Verdugo et al. (2020).

11 Results

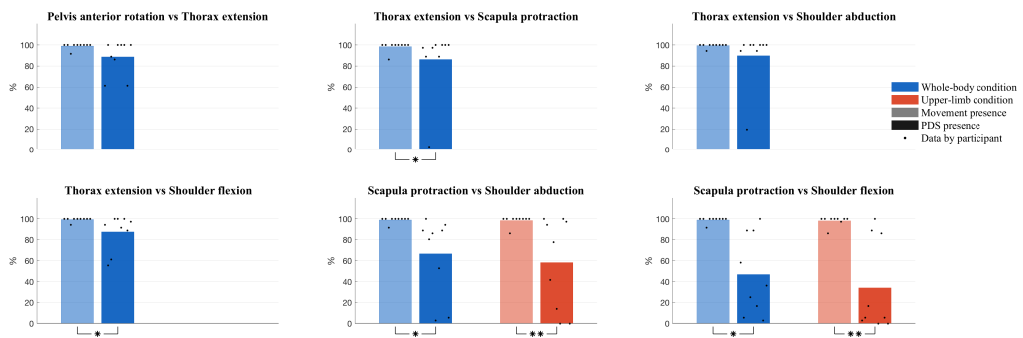
12 When movements were found, time-history velocity values across participants
13 depicted a PDS organization, *i.e.* the proximal movement decelerated while the distal
14 movement accelerated (Fig. 2). This was however not the case of the scapula/shoulder
15 pairs since their velocities increased and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

1 showed the smallest values across conditions and motion chains (scapula
 2 retraction = 12.76 ± 5.84 mm/s, shoulder extension = 7.96 ± 4.22 °/s) (Table 1).



3

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



9

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

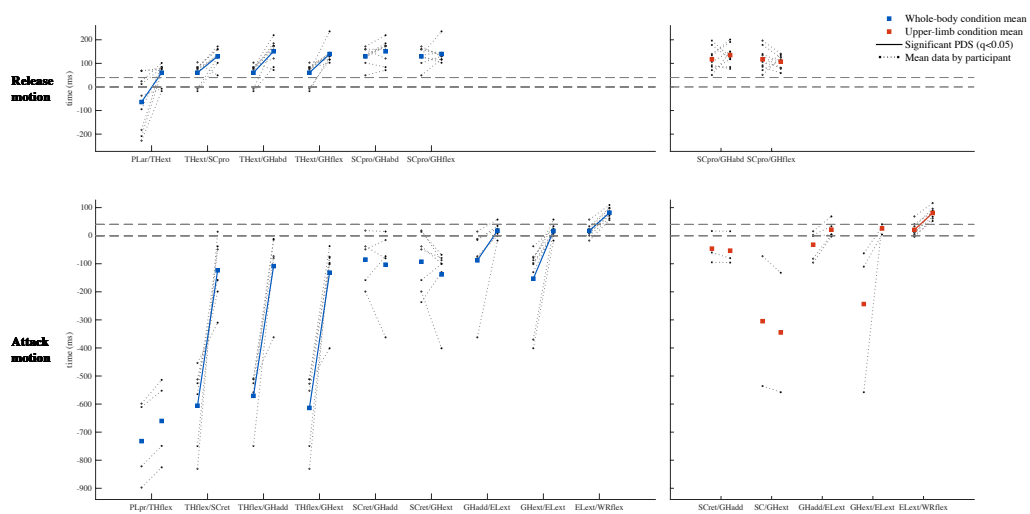
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1 The presence of movements according to our threshold increased in a proximal-
2 distal rationale during the attack chain (Fig. 3), whereas they were practically always
3 present during the release chain (Fig. 4). No significant differences were found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

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

24 In the attack chain, mean percentages across participants of movement presence
25 and PDS presence of scapula/shoulder and shoulder/elbow pairs showed overall higher

1 values in the *whole-body* than in the *upper-limb* condition (Fig. 3). Only movement
 2 presence of shoulder-extension/elbow-extension exhibited a significant difference
 3 between the two conditions ($q=0.031$). At the elbow/wrist pair, participants showed
 4 practically identical percentages (100%, and 97% in only one case) of movement
 5 presence and PDS presence during both conditions (Fig. 3). In the release chain, no
 6 significant differences were found between movement presence and PDS presence of
 7 scapula/shoulder pairs of the *whole-body* and the *upper-limb* condition (Fig. 4).



8
 9 Figure 5. Temporal organization of peak velocities during the attack and release motion
 10 chains by each experimental condition. Solid lines linking mean time values across
 11 participants illustrate a significant proximal-to-distal sequencing (no statistical test was
 12 executed for comparisons that exhibited $N < 5$). Horizontal dotted lines indicate the
 13 moment of the beginning of the attack ($t_0=0$) and an estimation of the end of the key
 14 descent (see caption of Fig. 2). PLpr = pelvis posterior rotation; PLar = pelvis anterior
 15 rotation; THflex = thorax flexion; THext = thorax extension; SCret = scapula retraction;
 16 SCpro = scapula protraction; GHadd = shoulder adduction; GHabd = shoulder
 17 abduction; GHext = shoulder extension; GHflex = shoulder flexion; ELext = elbow
 18 extension; WRflex = wrist flexion.

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

	<u>N</u>	<u>PDS%</u>	<u>q</u>	<u>Participants</u>								
<u>Attack motion: Whole-body condition</u>												
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
<u>Attack motion: Upper-limb condition</u>												
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
<u>Release motion: Whole-body condition</u>												
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
<u>Release motion: Upper-limb condition</u>												
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

3
 4 Note. p-Values were corrected (q value) with the false discovery rate procedure for
 5 multiple comparisons ($q < 0.05$). Bold q-values illustrate a significant proximal-to-distal
 6 sequencing. The column N indicates the number of participants used in the analysis (no
 7 test was performed when $N < 5$). The column PDS% shows the percentage of
 8 participants that exhibited a proximal-to-distal organization of the respective
 9 comparisons of mean time values. The column Participants indicates pianists where data

1 was found to perform the analysis. Bold d values illustrate a significant proximal-to-
2 distal sequencing.

3 **Discussion**

4 In this study, we evaluated expert pianists' PDS of key-attack and key-release
5 movements during isolated pressed-*staccato* keystrokes by analysing the temporal
6 organization of peak velocities from the pelvis to the wrist. In addition, we examined
7 the impact of trunk motion on PDS of upper-limb movements. Our results indicated the
8 presence of PDS during both attack and release multi-joint motion chains. Pianists' use
9 of PDS was however less clear between movements of the scapula and the shoulder,
10 where pianists showed signs of both PDS and distal-to-proximal sequencing. Pelvis and
11 thorax movements contributed to PDS of upper-limb movements by facilitating
12 shoulder-girdle movements, particularly shoulder extension, during the anticipation
13 phase of pressed keystrokes. In addition, trunk motion anticipated shoulder-girdle
14 movements during both attack and release chains.

15 ***Proximal-to-distal Sequencing: Key Attack***

16 Compared to struck touch, where the hand can be freely lifted over the keyboard before
17 the attack, pressed touch imposes greater spatiotemporal constraints because the
18 fingertip must remain in contact with the key before initiating the attack. Pressed touch
19 is however an important feature of piano performance, as it facilitates sound control by
20 generating a smoother key-descent acceleration than struck touch (Goebel et al., 2005).
21 Despite greater spatiotemporal constraints of pressed touch before the attack, we found
22 PDS of shoulder extension, elbow extension, and wrist flexion during the key-attack
23 motion chain as in the case of struck touch reported in Furuya and Kinoshita (2007)
24 (when these movements were performed, they practically always showed PDS). In

1 addition, we found that when performed, shoulder adduction also preceded elbow
2 extension. This indicates that potential interactions between shoulder, elbow, and wrist
3 movements before the attack could involve not only shoulder extension, as shown by
4 Furuya and Kinoshita (2007), but a complex downward anticipatory swing including
5 simultaneously shoulder extension and adduction.

6 Movements of shoulder-girdle joints were preceded by pelvis posterior rotation
7 and thorax flexion early during the anticipation phase. Our findings revealed significant
8 PDS of thorax/scapula and thorax/shoulder anticipatory movements, suggesting the
9 presence of a rationalized temporal motion organization of thorax and upper-limb
10 movements. Trunk movements occurred however early during the anticipation phase.
11 Mean timing differences across participants between thorax and shoulder-girdle peak
12 velocities (thorax-flexion/scapula-retraction=482 ms; thorax-flexion/shoulder-
13 adduction=462 ms; thorax-flexion/shoulder-extension=481 ms; see Fig. 5) were larger
14 than those reported in several sports (smaller than 100 ms, see *e.g.* Wagner et al., 2014).
15 These larger timing differences in pianists than in athletes might relate to the low
16 intensity character of piano performance compared to explosive sport activities.
17 Nonetheless, actual interactions between anticipatory thorax and shoulder-girdle
18 movements should be tested by future research focusing on kinetic analysis of piano
19 performance.

20 ***Proximal-to-distal Sequencing: Key Release***

21 Our results showed a PDS of pelvis, thorax, and shoulder-girdle movements during the
22 release motion chain in the *whole-body* condition. Specifically, pelvis anterior rotation
23 preceded thorax extension and thorax extension preceded scapula protraction and
24 shoulder flexion/abduction. Timing differences between thorax and shoulder-girdle
25 movements were smaller than 100 ms (thorax-extension/scapula-protraction=69 ms;

1 thorax-extension/shoulder-abduction=91 ms; thorax-extension/shoulder-flexion=79 ms;
2 see Fig. 5). These findings indicate a more similar PDS of pianists' release proximal
3 movements in relation to explosive sports activities (Wagner et al., 2014) than
4 anticipatory proximal movements. Shorter time differences between thorax and
5 shoulder-girdle movements were coupled with faster shoulder-girdle movements during
6 the release motion chain, as mean velocities were at least twice as fast compared to the
7 attack chain in both *whole-body* and *upper-limb* conditions (see Table 1). In a previous
8 study, we found that the release motion of *staccato* keystrokes induced an activation
9 burst of shoulder muscles during and after the attack (Degraeve et al., 2020). The
10 presented PDS of thorax and shoulder-girdle release movements should therefore be
11 further investigated by evaluating if motion-dependent interaction torques might
12 effectively occur between these movements and modify shoulder muscle load during the
13 production of loud *staccato* tones. Similar temporal sequencing of thorax extension and
14 shoulder-girdle movements could be investigated in other musical activities that involve
15 a burst of shoulder muscle activations, such as the up-bow phase of the violin bowing
16 movement (Shan et al., 2004).

17 By using multi-joint movements, pianists modulate not only hand and fingertip
18 velocities but also the effective mass applied to the key (Kinoshita et al., 2007), which
19 can involve the mass of the hand, forearm, arm, and torso. Evidence shows that expert
20 pianists mobilize the mass of the arm and torso in a forward rather than downward
21 direction during the key descent by using respectively *i*) shoulder flexion and scapula
22 protraction and *ii*) pelvis anterior rotation (Furuya and Kinoshita, 2008; Verdugo et al.,
23 2020). Therefore, these movements, which contribute to the production of PDS of the
24 key-release motion chain, play also a central role during the key-attack by controlling

1 the keystroke effective mass and, consequently, the targeted key velocity and tone
2 intensity.

3 ***Effect of Trunk Motion***

4 Temporal organization of multi-joint movements depends not only on expertise
5 but also on the specific characteristics of the task performed (Wagner et al., 2012). Our
6 results showed that expert pianists did not always perform the anticipatory movements
7 of shoulder-girdle joints. Mean presence of scapula and shoulder anticipatory
8 movements (attack chain) was overall higher during the *whole-body* condition, and a
9 significant difference was found specifically at the shoulder-extension/elbow-extension
10 pair (shoulder-girdle anticipatory movements also exhibited faster mean peak velocity
11 values when the trunk was mobilized as shown in Table 1). Thoracic posture affects
12 shoulder range of motion in standing (Barrett et al., 2016) and sitting positions
13 (Kanlayanaphotporn, 2014; Kebaetse et al., 1999). In our study, pianists increased
14 mobility of shoulder-girdle joints before the attack by using pelvis posterior rotation and
15 thorax flexion, which facilitated an anticipatory shoulder downswing usually not related
16 to pressed touch but to struck touch in studies on pianists' motor behavior (Furuya et al.,
17 2010). Indeed, according to the cited study, contrary to struck touch (which exhibited
18 use of proximal-to-distal inter-segmental dynamics), pressed touch was characterized by
19 effective utilization of distal-to-proximal inter-segmental dynamics. The authors
20 hypothesized that this difference was due to the stronger spatiotemporal constraints of
21 pressed touch, which requires instantaneous acceleration at the limb endpoint to
22 produce the targeted key velocity. Our findings show that trunk motion helps pianists
23 mitigate the increased spatiotemporal constraints of pressed touch by facilitating
24 shoulder movements before the attack (even if the fingertip must remain in contact with
25 the key). Therefore, a comprehensive kinetic study of pressed touch, which includes in

1 the analysis the utilization of trunk movement, would be necessary to develop a deeper
2 understanding of the complex motion interactions that might occur while producing
3 pressed keystrokes. Anticipatory trunk and shoulder-girdle movements were however
4 inconsistent across participants in both *upper-limb* and *whole-body* conditions (see
5 *e.g.* Table 2). We hypothesize that this inconsistency might be due to the greater
6 attention of piano performance approaches to attack and release movements compared
7 to proximal anticipatory movements (see *e.g.* Fink, 1992; Neuhaus, 1978).

8 ***Scapula and Shoulder Temporal Movement Organization***

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

1 ***Limitations and Future Research***

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

14 **Conclusion**

15 By analysing temporal sequencing of pianists' movements, this study showed the
16 presence of PDS from the pelvis to the wrist during the attack and release movements of
17 pressed-*staccato* isolated keystrokes. The use of PDS between scapula and shoulder
18 movements was less obvious, as pianists exhibited different temporal organizations
19 between these movements. We also showed that trunk motion facilitated PDS of
20 pressed-*staccato* keystrokes. On the one hand, it increased mobility of shoulder-girdle
21 joints during the anticipatory keystroke swing, thus mitigating motion constraints
22 related to pressed touch. On the other hand, it preceded the fast upward thrust of
23 shoulder-girdle joints associated with *staccato* and loud tones. Our study contributes to
24 a better understanding of expert pianists' multi-joint temporal organization of key-

1 attack and key-release movements. Implications relate to research on performance
2 optimization and injury prevention strategies.

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11 **Declaration of Interest Statement**

12 The author declare that this research was conducted in the absence of any conflict of
13 interest related to either commercial, financial or personal relationships.

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